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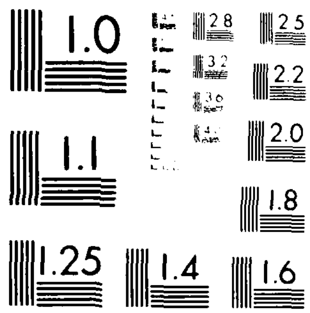

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Special Report 83-11

May 1983

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Effect of vessel size on shoreline and shore structure damage along the Great Lakes connecting channels

James L. Wuebben

Prepared for
DETROIT DISTRICT
U.S. ARMY CORPS OF ENGINEERS
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In conjunction with the Great Lakes connecting channels and harbors study, this report examines the potential damage to the shore and shore structures due to an increase in vessel size. The areas considered in this report are the United States shorelines along the St. Marys, St. Clair and Detroit rivers. The potential for shoreline or shore structure damage due to an increase in vessel size was reviewed on both a conceptual and site-specific basis. Ship-induced waves were ruled out as a damage mechanism since the analysis showed that the contemplated increases in vessel size would not significantly affect

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20. Abstract (cont'd)

wave heights in the nearshore zone. Propeller wash was discounted for similar reasons. Ship-induced drawdown was determined to be the major potential damage mechanism. While larger ships potentially produce more damage, this potential is significant only in severely restricted channel sections for the size increase considered here. By far the most significant factor in ship-related damage potential is vessel speed. In almost all areas the effect of an increase in vessel size could be eliminated by a reduction in vessel speed of 1-2 mph.

PREFACE

This report was prepared by James L. Wuebben, Research Hydraulic Engineer, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. It was funded by the Detroit District, Corps of Engineers under Contract No. NCE-IA-81-107 EK as part of the Great Lakes Connecting Channels Study. The report was technically reviewed by David Deck and Leonard Zabilansky, both of CRREL.

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These conversion factors include all the significant digits given in the conversion tables in the ASTM Metric Practice Guide (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	By	To obtain
feet	0.3048*	metres
inches	0.0254*	metres
knots	0.5144444	metres per second
miles	1609.344*	metres
miles per hour	0.44704*	metres per second
tons	907.1847	kilograms

*Exact.

EFFECT OF VESSEL SIZE ON SHORELINE AND SHORE STRUCTURE DAMAGE ALONG THE GREAT LAKES CONNECTING CHANNELS

James L. Wuebben

INTRODUCTION

This investigation was conducted in conjunction with the Great Lakes Connecting Channels Study. The overall study was undertaken by the Detroit District of the U.S. Army Corps of Engineers to examine ways of increasing the capacity of the Great Lakes waterways. This report examines the potential damage to the shore and shore structures due to an increase in vessel size. The areas considered are the United States shorelines along the St. Marys, St. Clair and Detroit rivers.

The largest ships currently using the Great Lakes waterways have a length of 1000 ft, a beam of 105 ft and a draft (set by a 27-ft authorized channel depth) of 25.5 ft. This study was undertaken to examine the effects of increasing the length to 1200 ft, the beam to 130 ft and the draft, in 1-ft increments, to 30.5 ft. The channel depths would be correspondingly increased from 27 to 32 ft.

This investigation uses basic theory and empirical data to determine regions within the study area where the hydraulic effects of an increase in vessel size might be significant. The analysis cannot predict the occurrence or magnitude of damage at those sites because of the interdependence of the effect of vessel size with uncontrolled factors such as water levels and vessel speeds. The result of the study is an estimate of shore areas that could be affected by an increase in vessel size.

BACKGROUND

There are several ways in which vessel passage might affect sediment transport and shore structures, including ship wave action, propeller wash, and other hydraulic effects. In addition, during navigation in ice, damage might occur by the direct movement of ice in contact with vessels, by disruption of natural ice-cover characteristics, and by interactions between ship-related water movements and the ice cover.

The significance of these various effects depends on a number of local conditions, such as bathymetry, water levels, soil conditions, ice conditions, shoreline and shore structure composition and geometry, ambient water currents, and waves.

In this section the significance of these various factors will be reviewed on a general basis to provide background for the site-specific analyses in later sections. Since the objective of this investigation is to analyze the significance of an increase in vessel size, a major effect of ship passage may not be considered significant for this report if the changes in vessel size considered here do not significantly alter the magnitude of the effect.

Ship waves

Waves are the mode of action normally associated with ship-induced damage in the nearshore zone. When a ship sails in ice-free, open water, a system of diverging and transverse waves develops. Diverging waves are those that form the familiar V-shaped wave pattern associated with ship passage. Transverse waves are oriented normal to the sailing line and form a less noticeable wave train that follows the vessel.

Due to the decay of the waves as they propagate and to the interaction of these two dissimilar wave sets, the generated wave heights are a strong function of position. In deep water these waves form a constant pattern and meet to form a locus of cusps at an angle of about 19°28' to the sailing line. This angle becomes greater in shallow water.

The maximum wave height occurs at the locus of the cusps. The wave heights at this locus decrease at a rate that is approximately inversely proportional to the cube root of the distance from the disturbance. Except in very shallow water this decay is caused primarily by the distribution of energy along the crest of the wave (Sorenson 1973).

The height of ship-generated waves is mainly a function of vessel speed (Gates and Herbich 1977). Table 1 gives the heights H_{max} of waves generated by boats with displacements from 3 to 5420 tons. These data were derived from measurements in the Oakland Estuary. Note the small range of wave heights generated at equivalent speeds by vessels of very different sizes and types.

Figure 1 was developed by Ashton (1974) from the data presented by Sorenson (1973). Although this figure ignores depth and draft effects, hull form and other parameters known to influence wave heights, there is remarkably little scatter. The figure shows the strong relation between wave height and ship velocity.

One method of estimating the height of a ship-generated bow wave in deep water is presented in Saunders (1957):

$$h = K_w \left(\frac{B}{L_E}\right) \frac{V^2}{2g} \qquad (1)$$

where h = height of the water surface at the bow (ft)

K_w = coefficient

B = ship beam (ft)

L_E = entrance length, or the distance from the bow to the parallel midbody (ft)

V = ship velocity (ft/s)

g = acceleration due to gravity (ft/s^2).

For cargo vessels with long, parallel midbodies, K_w is relatively constant at 1.133. The ratio B/L_E for a recently built 1000-foot Great Lakes ore carrier is about 0.67.

Equation 1 shows that if the vessel size were increased, the most extreme case would be to increase the beam of the ship while holding the entrance length constant. For the widest ship considered in this study this would result in

$$\frac{B}{L_E} = \frac{130}{156} = 0.833.$$

Using this assumption we may compare the effect of a change in vessel width with a change in vessel speed (Table 2).

Table 1. Selected ship-generated wave heights. (After Sorenson 1973.)

Vessel type	Length (ft)	Beam (ft)	Draft (ft)	Displacement (tons)	Water depth (ft)	Speed (knots)	H_{max} (ft) Distance from sailing line (ft) 100	500
Cabin cruiser	23	8.3	1.7	3	40	6	0.7	0.4
						10	1.2	0.8
Coast Guard cutter	40	10	3.5	10	38	6	0.6	1.0
						10	1.5	
						14	2.4	
Tugboat	45	13	6	29	37	6	0.6	0.3
						10	1.5	0.9
Converted air-sea rescue vessel	64	12.8	3	35	40	6	0.3	
						10	1.4	0.8
						14	2.0	1.1
Fireboat (converted tug)	100	28	11	343	39	6	0.4	0.2
						10	1.7	1.0
						14	3.1	2.6
Barge	263	55	14	5420	42	10	1.4	0.7

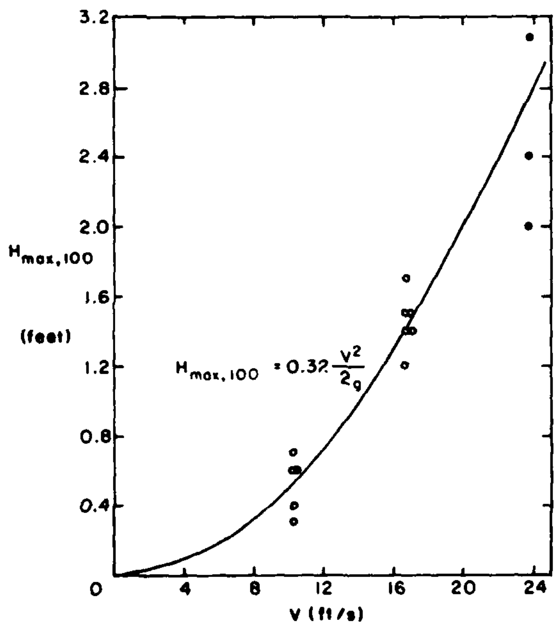


Figure 1. Maximum wave heights 100 feet from the sailing line for a variety of hull forms. (After Ashton 1974.)

Table 2. Effect of vessel size and speed on bow wave height.

B (ft)	L_E (ft)	B/L_E	V (ft/s)	h (ft)
105	156	0.67	5	0.30
			10	1.17
			12	1.70
130	156	0.833	5	0.37
			10	1.46
			12	2.11

Thus, estimating the height of the water surface at the bow by this method (and using a conservatively blunt bow) indicates that at a velocity of 10 ft/s the contemplated increase in vessel size shown in Table 2 might increase the wave height by about 0.3 feet. If the velocity of a 105-foot-wide ship was increased from 10 to 12 ft/s, the wave height would increase by over 0.5 feet.

While the magnitude of the wave heights calculated above should not be considered accurate for conditions in the areas of concern to this report, they do indicate that vessel speed is much more important than vessel size and geometry for the range of ship sizes considered here. Also, these calculated wave heights are near-ship values. Since bow waves decay in approximately inverse proportion to the cube root of the distance from the sailing line, the wave heights and the differences between wave heights will be reduced significantly as the waves propagate away from the ship.

Another important consideration is the water depth. This has been treated by using the ratio of water depth to ship draft (Johnson 1958). As the depth d becomes shallower relative to the draft D, wave heights change. However, for the change in sizes contemplated here, d/D varies only from 1.049 to 1.058, which may be neglected.

A joint study by the Detroit District, U.S. Army Corps of Engineers and the St. Lawrence Seaway Authority (USACE and SLSA 1972) was conducted to measure wave heights on the Detroit and St. Clair rivers. In analyzing their data they differentiated only between upbound and downbound vessels (which reflects the relative velocity in a river system) and between ocean-class and inland ships.

In their analysis they fitted analytical curves to their field data, which showed some scatter. Although they did not examine the effect of

vessel size, they compared the wave heights generated by ocean versus inland ships (Fig. 2). This distinction reflects a basic difference in hull geometry; in addition, inland ships tend to be larger. Figure 2 shows that the difference in wave heights developed from field measurements for the two classes of ships is slight. The figure considers only upbound ships along a channel that is roughly 3500 feet offshore.

Figure 3 includes inland vessels only. Here, however, the water has a velocity of about 1.3 mph, which accounts for the difference in wave heights for upbound and downbound ships. The channel is roughly 3500 feet offshore.

Figure 4 also compares the wave heights of upbound and downbound ships, but here the sailing line is only about 400 feet offshore. This results in higher waves than shown in Figure 3. The water velocity in the area averages 2.2 mph.

In summary, while ship-generated waves can cause significant damage to the shoreline and shore structures, the change in vessel size considered here is not great enough to cause a significant change in wave size. Ship speed is far more important in determining wave size than is ship size or geometry.

Finally, waves produced by large-scale navigation are generally much smaller and less damaging than those produced by recreational craft, particularly when vessel speed and distance to the shore are considered. A recreational craft traveling near the shore at just below planing speed may deliver a much more damaging wave than a large vessel offshore in the navigation channel. Wind-driven waves can also be significant, because of their size and especially because their duration is much greater.

Propeller wash

During vessel passage the bottom and possibly the sides of a channel may be subjected to a propeller-driven water jet. There has been very little study of sediment transport due to propeller wash, and there were no data available for the areas considered in this report. An assessment of the effect of a change in vessel size on this aspect of sediment transport is not yet possible due to a lack of information on the relationships among propeller geometry, speeds and other factors.

Fortunately propeller wash, which is a relatively localized effect in the navigation track, should be insignificant for the purpose of this

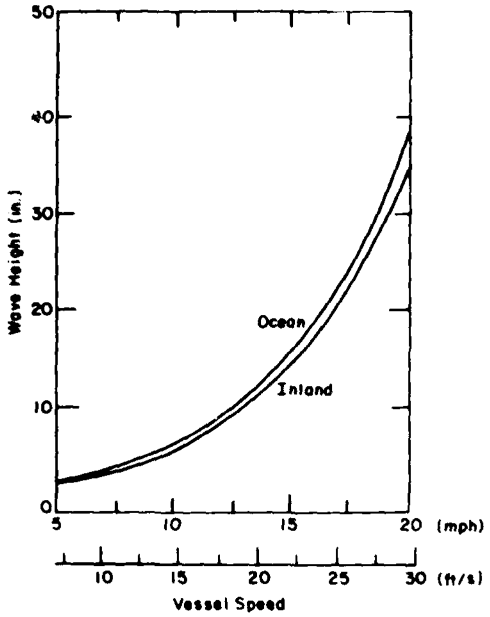


Figure 2. Comparison of wave heights generated by ocean and inland ships. (After USACE and SLSA 1972.)

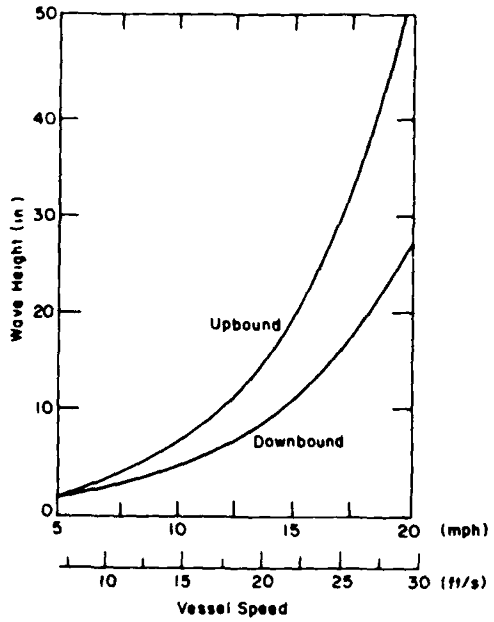


Figure 3. Comparison of wave heights for upbound and downbound ships at Grosse Point, Michigan. (After USACE and SLSA 1972.)

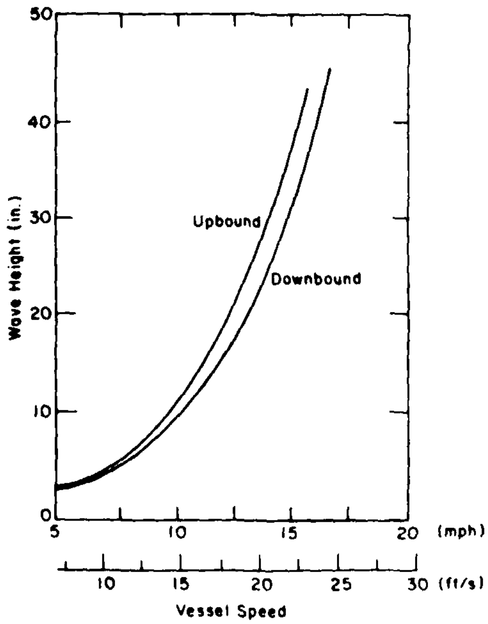


Figure 4. Measured ship wave heights for upbound and downbound ships at Sans Souci. (After USACE and SLSA 1972.)

study. Since we are concerned with the potential for damage in the near-shore zone, the effect of a change in ship thrust resulting from a change in vessel size can be neglected.

Hydraulic effects of ship passage

Although ship waves and other hydrodynamic effects of vessel passage have been studied in terms of vessel maneuverability and power requirements, the effects of vessel passage on natural flow patterns and distribution and other environmental factors are not yet understood. Information for periods of ice cover is almost nonexistent.

When a vessel is in motion, even in deep water, the water level in the vicinity of the ship is lowered, along with the ship itself (this is called vessel squat). This effect increases as the vessel's speed increases or as the water depth decreases. When a ship enters restricted water areas, there is a considerable change in the flow pattern about the hull. In shallow water the water passing beneath the hull must pass at a faster rate than in deep water, and as a result there is a pressure drop beneath the vessel, increasing vessel squat. In a channel that is restricted laterally, vessel squat is also exaggerated; the bow of a vessel may also be pushed away from one side of the channel while the stern is drawn toward it. These effects can occur independently when a channel is restricted laterally or vertically and unrestricted in the other direction.

There is, however, another problem associated with the water level drop caused by the presence and movement of a ship in restricted waters. This water level drop is, in effect, a trough extending from the ship to the shore and moving along the river or channel at the same velocity as the ship. As the ship's speed increases, the moving trough deepens.

For the restricted sections of the Great Lakes channels, this effect might most easily be envisioned as a channel constriction. The conservation of energy principle applied to subcritical flow in an open channel as the flow passes through a channel constriction indicates that the water surface will drop as the flow passes through the constricted portion of the channel.

The energy relation (neglecting losses) takes the form of

$$\frac{V_1^2}{2g} + Y_1 = \frac{V_2^2}{2g} + Y_2 \qquad (2)$$

where

V_1 and Y_1 = velocity and depth prior to the constriction

V_2 and Y_2 = velocity and depth within the constricted passage

g = acceleration due to gravity.

This is combined with the continuity relation:

$$Q = A_1V_1 = A_2V_2 \tag{3}$$

where Q is the discharge and A_1 and A_2 are areas available for flow before and within the constriction, respectively. Before eqs 2 and 3 can be applied in this form, the unsteady flow with the passage of a ship should be converted to steady flow by adding a velocity vector to the flow sections equal but opposite to the vessel speed.

The phenomenon of nearshore drawdown and surge during vessel passage may be explained in terms of the moving trough. In sufficiently deep water the moving trough appears as a fluctuation of the elevation of the water surface. To an observer in a shallow or nearshore area where the depressed water level approaches or reaches the riverbed, the water level appears to recede from the shoreline as the ship passes; this is followed by an uprush and finally a return to the normal level after the vessel-induced surface waves are damped.

Using the energy-continuity model it is possible to have critical flow in the constricted area between ship and shore. Energy considerations require the water level to rise in front of the ship before the trough develops if the ship's speed is increased beyond that required for the initiation of critical flow. An observer on the shore would then see the water level rise before observing the effects of the moving trough.

Measurements and observations

The water level and directional water velocity were measured at a number of locations along the St. Marys, St. Clair and Detroit rivers under different conditions as ships passed. Some of this information is presented here to illustrate the effects of vessel passage.

To analvze the mechanics of sediment transport during vessel passage, two-dimensional, near-bottom velocity measurements were made. An example of these measurements is presented in Figure 5 for a passage of the *Cason J. Callaway* at Six Mile Point on the St. Marys River. The point of observation was approximately 500 feet offshore in 10 feet of water, while the navigation track was another 700 feet offshore. The ambient downstream

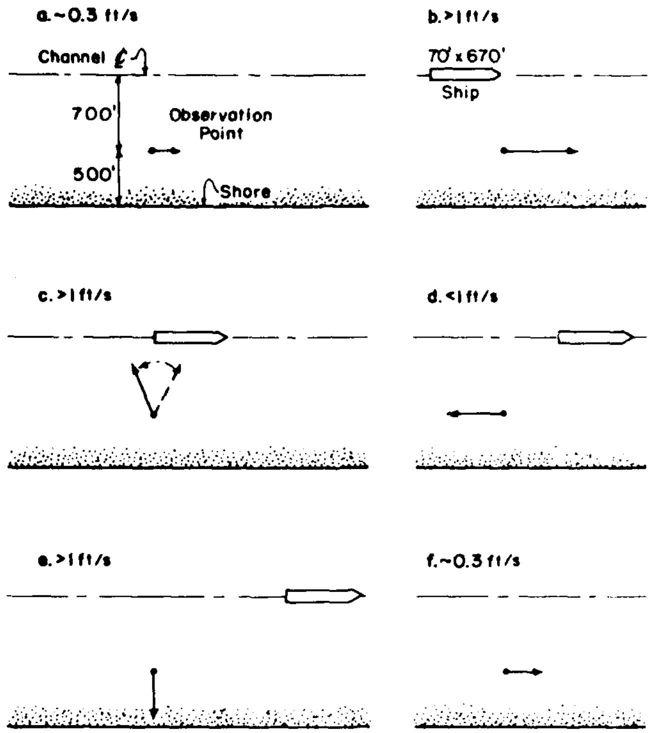


Figure 5. Ship-induced water movements.

water velocity was approximately 0.3 ft/s. The direction of the near-bottom water movement rotated 360° during the passage of the Callaway, with velocities in all directions significantly greater than the ambient down-stream current.

Figure 6 illustrates the trough effect near the shoreline and the complex velocity pattern that developed at an offshore point because of vessel passage. The velocity direction at any particular point is indicated by an arrow, with the magnitude of the velocity and time as the axes.

The velocity meter was located approximately 130 feet from the shore in 3 feet of water. The velocities shown were measured within 8 inches of the bottom. The water-level gauge was located near the shore in about 8 inches of water. The ship that caused the situation illustrated in Figure 6 was the J. Burton Ayers, moving upriver near Nine Mile Point on the St. Marys River under ice-free conditions. The Ayers is 620 feet long and has a 60-foot beam and a midship draft of 23 feet. The vessel was traveling at 15.5 ft/s and passed approximately 800 feet from the shore.

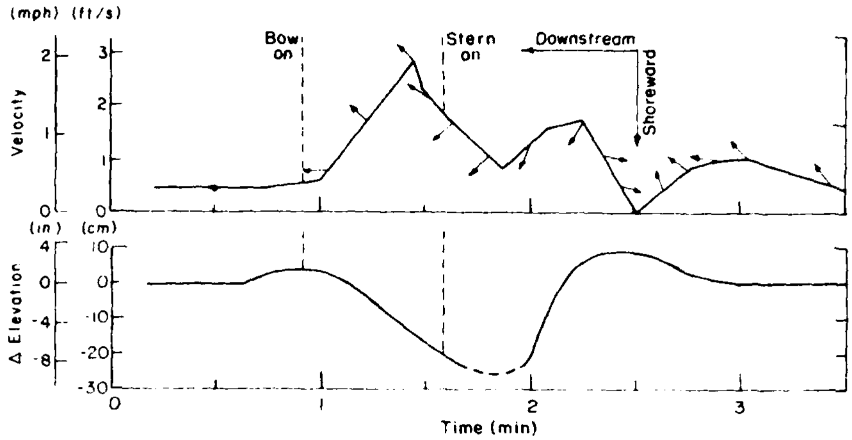


Figure 6. River level and near-bottom velocity pattern with an upbound ship. (From Wuebben et al. 1978.)

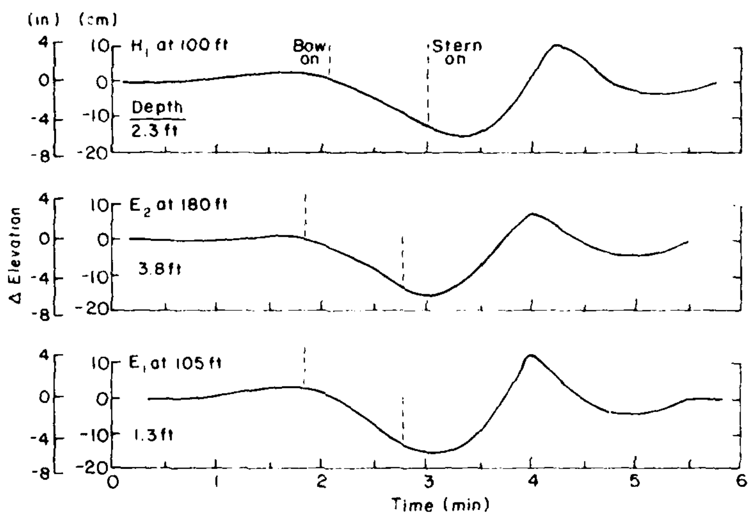


Figure 7. Ice-level changes with an upbound ship. (From Wuebben et al. 1978.)

Figure 7 shows ice-level changes at three offshore locations near Six Mile Point on the St. Marys River. There was an ice cover on the river approximately 15 inches thick. The ship passing the section was the Seaway Queen, moving upriver at 12.6 ft/s. The ship is 720 feet long, with a beam of 72 feet and a midship draft of 17 feet. It passed 1000 feet offshore. The typical river cross section at this location is shown in Figure 8.

The two lower curves in Figure 7 illustrate ice-level changes at two distances from the shore on a line approximately normal to the direction of ship movement in different depths of water (labeled E_1 and E_2). The top

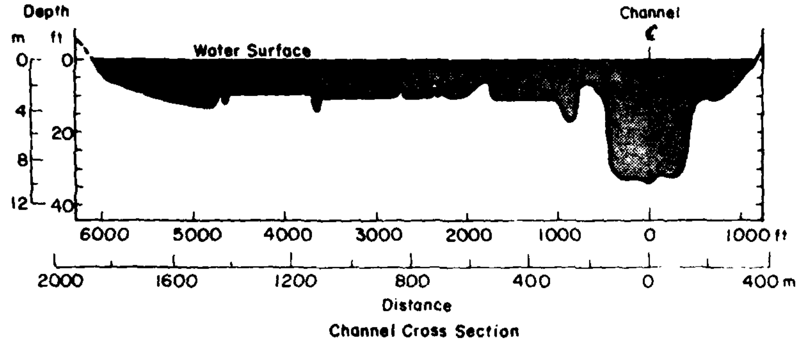


Figure 8. Cross section of the St. Marys River near Six Mile Point.

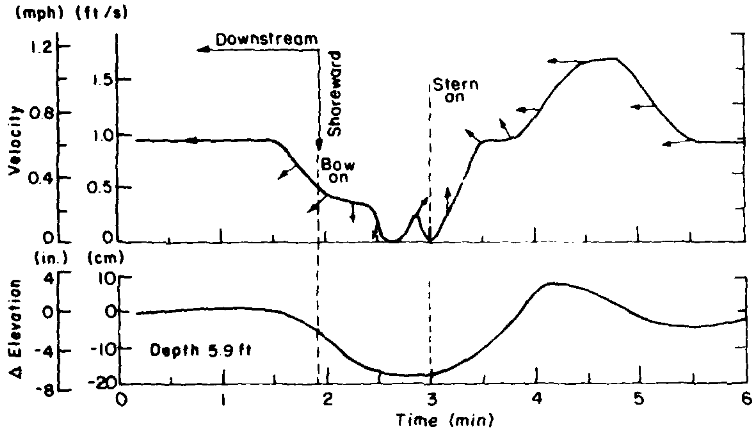


Figure 9. River level and near-bottom velocity pattern with a downbound ship. (From Wuebben et al. 1978.)

curve (labeled H_1) shows the ice-level change at a point 150 feet upstream on a line parallel to the line containing points E_1 and E_2. The time at which the bow and stern crossed the perpendicular range line (E or H) is indicated by dashed lines. The figure illustrates the trough effect in different depths of water at differing distances from shore, as well as the movement of the trough with the ship's passage. The time displacement between E_1 and H corresponds to the distance between the two range lines divided by the ship's speed.

Figure 9 shows ice-level changes (the ice was 11 inches thick) and the associated velocity pattern near the bottom as the Edward L. Ryerson passed downriver. The range line is the same as E in Figure 7. The ice level and

velocity pattern were measured about 300 feet from the shore, where the river depth is about 6 feet. The ship is 730 feet long, has a beam of 75 feet and a draft of approximately 26 feet, and was traveling at 10.3 ft/s about 1000 feet offshore. Figure 9 illustrates the velocity pattern and the ice-level response to the moving trough for a downbound vessel. Ice-level fluctuations as large as 2.6 feet from trough to crest have been observed.

CONCEPTUAL ANALYSIS

Before proceeding to a site-specific analysis of the effects of an increase in vessel size, we will evaluate an idealized system to define site characteristics subject to potential damage. Because we are looking only for damage due to an increase in vessel size, vessel-related damage mechanisms are not considered if the potential for damage is not substantially increased by a change in vessel size. On this basis drawdown and surge are considered to be the major potential damage mechanisms. For the long, parallel-midbody ships considered in this study, vessel length is insignificant. Increases in vessel draft and beam are the primary problems. In the theoretical calculations that follow, a one-dimensional model is being used for examining the effects of changing the various ship and channel dimensions to show their relative importance within the expected ranges of these parameters.

Effect of increasing vessel draft

The first change in vessel size we will examine is increasing the allowable draft, which implies deepening the channel. Although we do not have detailed information as to the geometry of the proposed deepened channels (channel width, side slopes), we can examine the effect for ideal cases.

With the exception of the Rock Cut Channel on the St. Marys River, the connecting channels of the Great Lakes have the following minimum dimensions: the top width T is 1,000 feet, the channel depth d is 27 feet, the cross-sectional area A_c is 20,000 square feet, and the shape factor S_f is between 0.2 and 1.0. The shape factor is defined as

$$S_f = \frac{A_c}{d \cdot T} . \qquad (4)$$

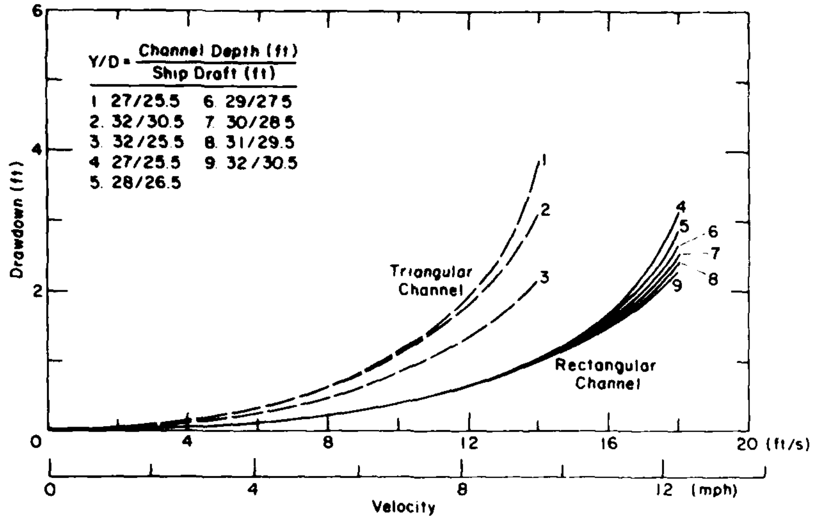


Figure 10. Effects of channel depth and ship draft on drawdown.

Thus, for a rectangle S_f is 1, for a triangle it is 1/2, and for a parabola it is 0.67.

Taking the channel dimensions listed above as conservative estimates of minimum channel dimensions, we can conceptually examine a "worst case" using an analysis based on the energy and continuity relations mentioned earlier (eqs 2 and 3).

Figure 10 examines the effect of channel depth and ship draft on drawdown for the ideal cases of rectangular and triangular channels. Many natural channels lie between these cases. The curves for a rectangular channel represent the various proposed channel depths for different vessel drafts. Even at a relatively high speed of 17 ft/s, where the drawdown would be an unacceptable 2 feet, the difference in drawdown between existing conditions and the maximum proposed draft would be less than that due to a change in vessel speed of only 1 ft/s.

More important, increasing channel depth and ship draft would decrease the magnitude of the drawdown and the potential for damage. This occurs because an increase in draft of a ship 105 feet wide adds far less area to the ship than a corresponding increase in channel depth over the width of channel. Even for a narrow, dredged channel the channel width will be at least several times wider than the ship's beam.

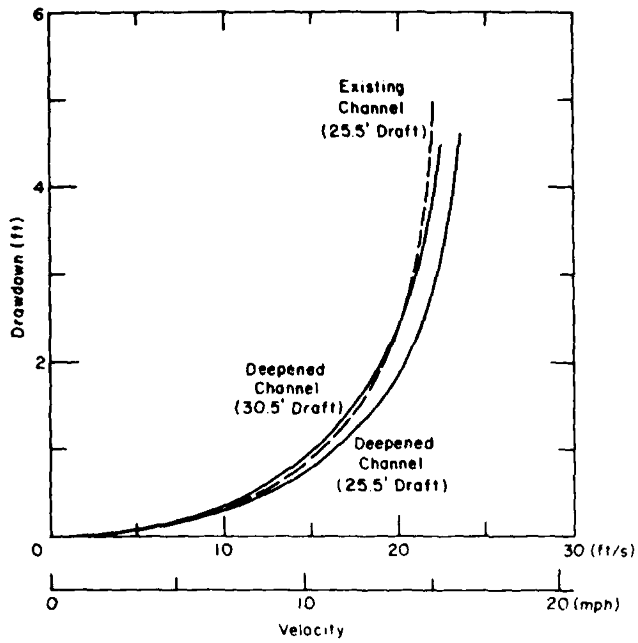


Figure 11. Effects of channel depth on drawdown at Frechette Point on the St. Marys River.

The second group of curves in Figure 10 corresponds to a triangular channel and shows greater drawdown than does the rectangular channel. This is to be expected, because the cross-sectional area would be smaller for the same depth and top width.

The important feature to note from these curves is that when the channel depth is increased, drawdown decreases, even if the ship draft is correspondingly increased. Further, for ships that cannot increase their loading to the new maximum permissible draft, drawdown is drastically reduced.

If we examine an actual cross section from a dredged channel on the St. Marys River, the effect of deepening the channel is even less significant. Figure 11 illustrates the effect of deepening the channel near Frechette Point from 27 to 32 feet. The curve in Figure 11 representing an increase in both channel depth and ship draft is almost identical to existing conditions. A ship at the existing maximum safe draft would have to travel much faster in the deepened channel to create the same drawdown.

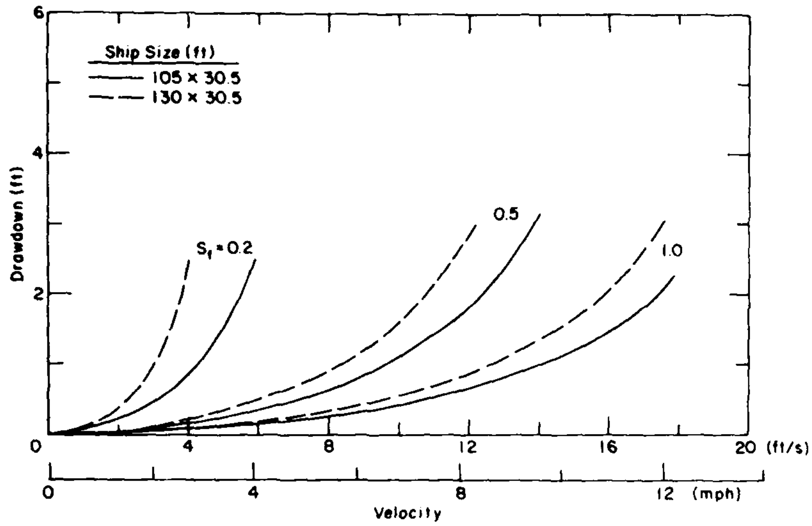


Figure 12. Effects of increasing ship beam on drawdown.

<u>Effect of increasing vessel beam</u>

If we again assume the minimum channel cross sections used in the previous section, we can examine the effect of an increase in vessel width by considering ships 105 and 130 feet in beam at the various safe drafts.

Figure 12 shows the extremes of proposed vessel sizes in a 32-foot-deep channel of various shapes. This figure shows that an increase in the width of the ship can have a significant effect on the magnitude of drawdown. Even at the modest vessel speed of 10 ft/s, increasing the ship's beam to 130 feet would increase the drawdown by about one-half foot in a triangular channel ($S_f = 0.5$). Many portions of the St. Marys River have shape factors much less than 0.5, making the effect even greater. However, these areas also have much wider cross sections than that considered in Figure 12; this would reduce drawdown.

Figure 13 compares the combined effects of an increase in ship beam and draft as well as channel depth. The river width at the surface is again 1000 feet, while the shape factor is 0.67 (a parabolic section), comparable to the natural channel along most of the Detroit and St. Clair rivers. It is apparent that the proposed change in ship beam is much more significant than the change in vessel draft and channel depth.

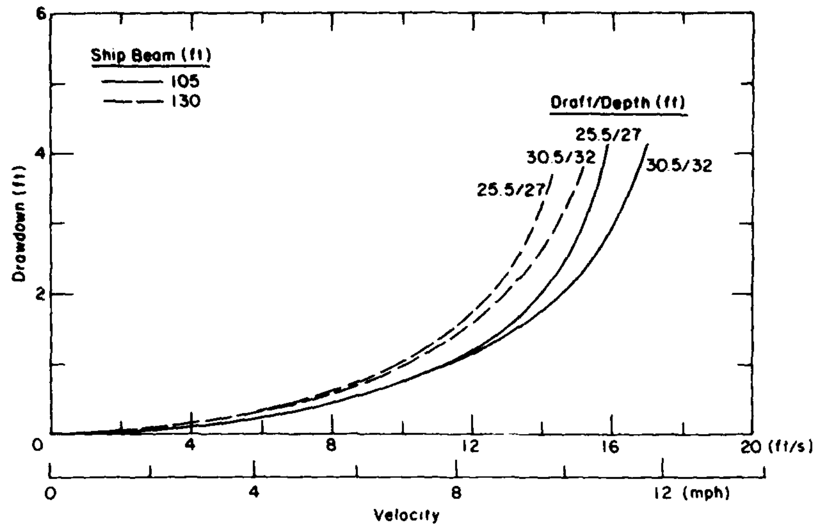


Figure 13. Effects of ship and channel depth on drawdown.

Sensitivity of drawdown mechanism

In the preceding sections we have examined the effects of proposed changes in vessel size in relative isolation. We can also view the relative importance of the pertinent variables by examining the deviations they cause from an ideal case. Again, we are using a one-dimensional model to examine the relative importance of the parameters for the expected ranges of variation.

We will call the basic case a ship with a 25-foot draft and 100-foot beam traveling in a rectangular channel 35 feet deep and 2000 feet wide. The ship velocity relative to the water is 12 ft/s. This case is plotted as the central point on Figure 14.

Figure 14 shows that the effect of deepening a channel is roughly equivalent to increasing the vessel draft. Also, a 5-foot change in draft would have a larger effect than a 5-foot change in vessel beam. However, while the proposed change in vessel draft is 5 feet, the proposed change in ship beam is 25 feet, which would make it slightly more significant. In addition, increasing the ship draft requires an increase in the channel depth, which would effectively cancel the effect of an increase in draft. No corresponding change in channel width is envisioned.

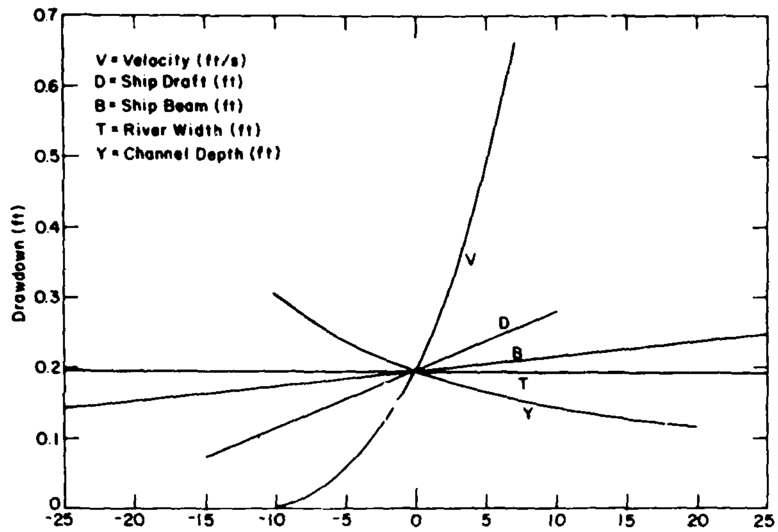


Figure 14. Effects on drawdown due to variation in parameters from the basic case.

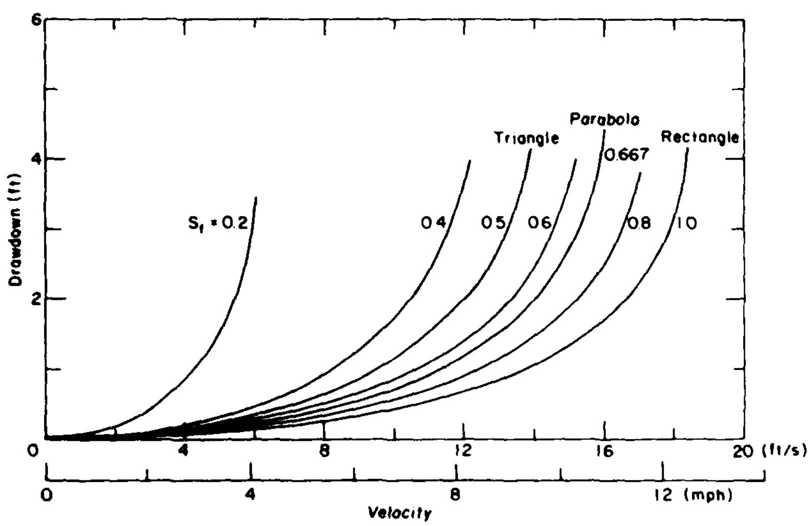


Figure 15. Effect of channel shape on drawdown (the river top width and channel depth are constant).

It is also evident that for the ideal case shown in Figure 14, an increase in vessel speed of only 1 ft/s would be roughly equivalent to the extremes of ship and channel dimension changes considered. Vessel speed control is clearly far more important than the changes in vessel size considered for this report.

Effect of channel shape

Figure 15 illustrates the drawdown for a single ship passing through channels of equal top width and channel depth but varying shape factor. Other values being equal, a ship passing through a typical natural channel (roughly parabolic) would cause a greater disturbance than if it passed through a rectangular channel but less than in a channel similar to some sections of the St. Marys River, where the shape factor might be as low as 0.3. While this observation appears simple, it is important in understanding why the effects of ship passage are much more severe on the St. Marys River than on the other connecting channels. A similar argument can be made for channel width.

POTENTIAL FOR SHORELINE DAMAGE

The potential for shore damage due to vessel passage is a direct function of the change in hydraulic conditions initiating sediment transport or increasing transport rates. Enhanced sediment transport due to such a localized disturbance typically results in riverbed scour or shoreline erosion.

For sediment transport to occur, near-bottom or nearshore water velocities must overcome a sediment particle's resistance to motion. These water velocities may be due to ambient river conditions, wind-driven waves, general turbulence, or ship-induced effects, among others, and they might be enhanced by channel configuration or ice irregularities. During vessel passage large and rapid changes in river velocity and direction can occur.

Three modes of transport of granular bottom sediments have been observed during both ice-covered and ice-free conditions (Wuebben et al. 1978). They are 1) bed load, which is typified by a pattern of slowly migrating sand ripples on the riverbed, 2) saltation load, the movement of individual sand grains in a series of small arcs beginning and ending at the riverbed, and 3) explosive liquefaction, in which bottom sediment is rapidly resuspended due to a rapid change in the pore-water pressure gradient.

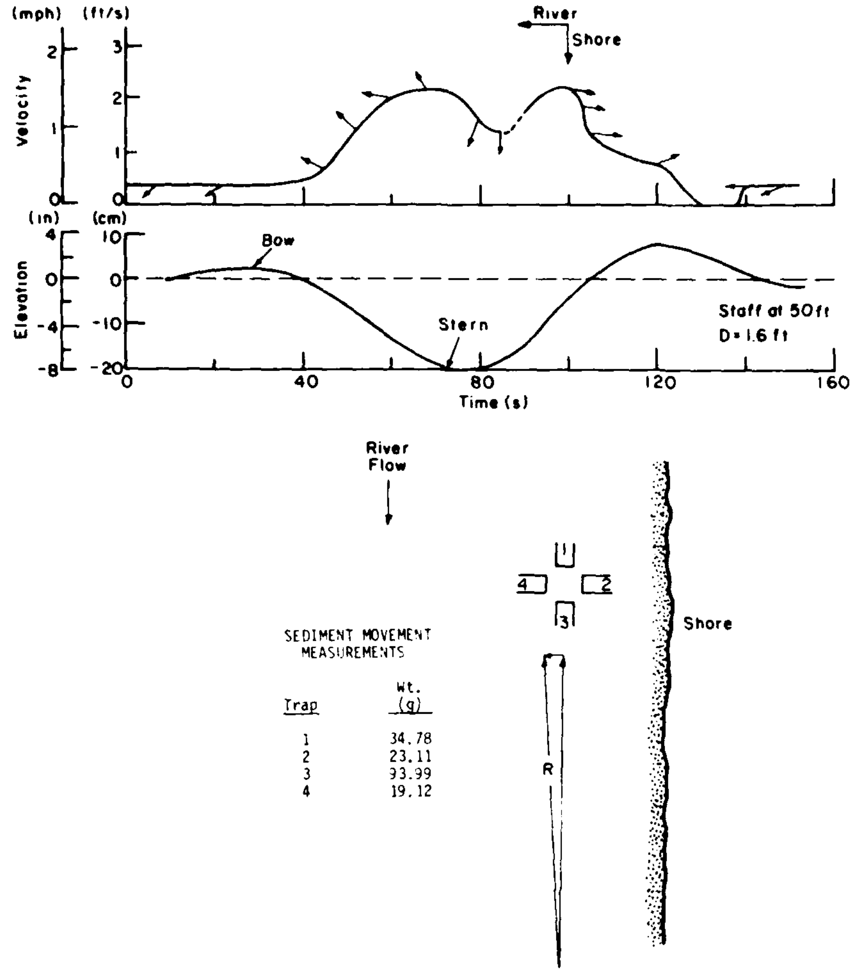
Vessel passage affects the magnitude of bed load transport, and it also causes significant (but temporary) changes in the direction of sand ripple migration. Saltation transport has often been observed with the passage of large vessels. This can be explained by the ship-induced velocity increases discussed earlier.

In addition to these alterations in water velocity, the changes in water surface elevation during ship passage can occur more quickly than the pore pressure in the riverbed soil can adjust. If the decrease in water pressure on the riverbed during the passage of the moving trough occurs faster than the change in soil pore pressure, a net uplift force on the soil near the surface will occur. After the trough passes and the water level rises, the process reverses and there is a net downward force on the riverbed sediment. As the ship passage cycle is repeated, this mechanism, in conjunction with gravity acting downslope, encourages a net offshore migration of sediment that is in addition to any transport due to water velocities alone.

On several occasions, explosive liquefaction has been observed on the St. Marys River during the passage of large, heavily loaded vessels at speeds higher than normal. Explosive liquefaction of the bed has been observed by divers working in the surf zones of lakes and oceans, and often may also be observed from shore as waves break. In the presence of a reasonably horizontal velocity field, the action occurs in two steps. Initially the bed expands upward somewhat. Immediately the uppermost part of the bed disperses into suspension, and the temporarily suspended mass moves in the water current. In the absence of a current the bed simply quakes or expands, and individual particles move upward. Bed equilibrium is rapidly reestablished by gravity.

Since the drawdown and surge mechanism usually sets up water velocities in opposite directions, their effects tend to cancel. However, natural currents or a sloped bottom can combine with vessel effects to cause a net sediment transport upstream or downstream and offshore towards the navigation channel.

Figure 16 shows velocity and stage measurements at Nine Mile Point on the St. Marys River (Alger 1978). Sediment transport was also measured for this passage. The vessel was the Sir James Dunn moving upriver at 10 mph.



Trap	Wt. (g)
1	34.78
2	23.11
3	93.99
4	19.12

Figure 16. Velocity, stage and sediment movement measurements at Nine Mile Point during passage of the <u>Sir James Dunn</u>. (After Alger 1978.)

The sand bottom began to move at about 65 seconds, at which time the velocity pattern was downriver and offshore and the water level was dropping rapidly. The back side of the trough followed, with a generally upstream velocity pattern.

A pattern of four sediment traps was used to measure sediment transport. One trap faced upriver, one toward the shore, one downriver and one away from the shore (Fig. 16). The traps were calibrated over a 20-minute period with no boat traffic; none of the traps collected any sediment in this ambient condition. The sediment traps were also placed at this location on a day when wind waves of about 1-foot amplitude were present

without vessel passage. All traps collected sediment. Waves due to winds were negligible as the Sir James Dunn passed. The traps were left in place as the Sir James Dunn passed and were removed immediately afterward to retrieve any sediment collected. The sediment in each trap was carefully weighed (Fig. 16). The traps were located near the staff gauge at 50.5 feet in 1.6 feet of water. Field observations and the velocity-stage relations for upbound vessels at this site show that bottom sediment moves both downstream and upstream during vessel passage; however, the apparent net effect is upstream and slightly offshore, as indicated by the vector diagram of sediment trap load shown on Figure 16. This, of course, assumes that a vessel produces sufficient drawdown and velocity to move the bottom materials.

A composite sample from the four traps was analyzed for size gradation. The results show the same soil properties as the upper few centimeters of the bottom. Apparently, this vessel passage translocated all soil sizes at this location.

Another sediment transport mechanism operates when material is carried out of a cell (or restricted area). Cells include small bays and the heads and tails of islands. In small bays, sediment in shallow water may be moved around a point of land or into deeper water where the vessel effect is not as pronounced, allowing the sediment to settle. This may be the cause of the reported deepening of small bays. At the head or tail of an island or at a point of land, vessel effects may transport sediment around the point. The land then shields the sediment from further vessel effects.

The role of ice in sediment transport and shoreline erosion has many facets. The most obvious effect is that ice formed on a shore or riverbank may isolate and thereby protect the shore. Ice formations can, however, cause significant localized damage by gouging ordinarily stable beach or bank formations, by removing protective vegetation, by adfreezing sediment at the ice/soil interface, and by entraining sediment within the ice structure. However, the proposed changes in vessel size should not affect these processes.

Another consideration is the effect of ice on the general hydraulics of a system. In a river, an ice cover changes the open channel conditions into a form of closed conduit flow, changing the velocity profiles and distribution. The added boundary shear due to the ice cover decreases flow

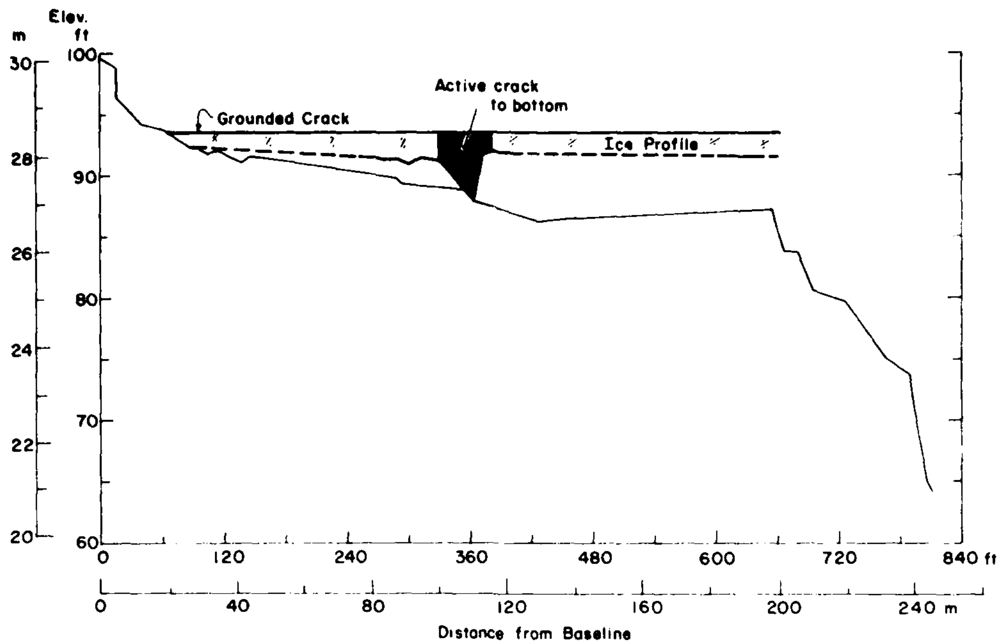


Figure 17. Shore and ice profile, St. Marys River.

velocities and increases flow depth. Although there may be anomalies, an ice cover and winter conditions will tend to reduce sediment discharge. Ice jams, frazil dams or other ice irregularities causing a constriction or deflection of flow may result in damage.

Shore damage due to the lateral movement of ice induced by vessel passage is ordinarily small and limited to early or unstable ice conditions and to shore areas close to the navigation track. During spring breakup, larger, more massive ice floes may act on a shore, but with higher temperatures the ice is usually deteriorated and weaker.

Shore damage due to horizontal ice movement, while possibly significant, is unpredictable, infrequent and difficult to quantify. A long length of shoreline may be affected over a period of years, but only a small portion might be affected in any one year. As a result, structural shore protection would be difficult and most likely uneconomical to apply. Regulating vessel traffic in affected areas having certain ice conditions may best mitigate the damage. The proposed change in vessel size should have little effect on these processes.

During winter ice conditions, the drawdown due to vessel passage can cause an ice cover to ground in shallow water and nearshore areas, and nearshore cracks in the ice may develop running roughly parallel to the

water depth contours. With recurring, moderate water-level fluctuations, these hinge cracks do not completely refreeze and can provide an ice-movement relief mechanism. Continuing vertical and horizontal movement of the ice cover may cause the accumulation of ice debris (which resembles pressure ridges) at these active cracks (Fig. 17). Depending on the characteristics of crack formation, ice dams extending to the riverbed may develop at the cracks.

POTENTIAL FOR SHORE STRUCTURE DAMAGE

The objective of this section is to evaluate the change in incidence of damage to shore structures resulting from a change in vessel size. Damage could occur due to water currents, water-level fluctuations or ice movement. Structural damage due to ship-induced water currents is insignificant, so any contribution due to a change in vessel size will be negligible.

Structures may be damaged by ship-induced waves during open water conditions. However, this damage mechanism is typically caused by and limited to excessive vessel speed. If sound speed limits are enforced, damage to shore structures should be minimal. As discussed in an earlier section the contemplated changes in vessel size should have only a small influence on the size of open-water waves. The most damage may be caused by ship-induced drawdown, particularly drawdown during periods of ice cover.

The degree to which the shore structures of the Great Lakes system are damaged by ice varies greatly according to the manner of ice action. Winter navigation, by disrupting the normal ice-cover characteristics, may aggravate any natural ice-related damage.

Ice effects on structures typically fall into one of the following categories:

1) Static ice forces, which arise from an ice sheet touching a structure subject to thermal expansion and contraction or subject to steady wind or water drag forces.

2) Dynamic ice forces, which arise from ice sheets or floes that move against a structure due to water currents or wind, or

3) Vertical ice forces, which are due to a change in water level and require the adhesion of floating ice to structures.

For small structures in rivers the dynamic horizontal and vertical ice forces are typically the most critical. A more detailed discussion of this topic may be found in Wuebben (In press).

Horizontal ice forces. Depending on the size and strength of an ice floe, the horizontal force exerted on a structure depends on the strength of the ice sheet and its failure mode (bending, crushing or shearing) or the magnitude of the force driving the ice sheet (wind or water current).

Forces on shore structures due to direct horizontal ice loading are controlled more by the frequency of vessel passage than by the size of the vessel. Typically ships do not directly transfer forces to a structure through the ice unless they come very close to shore. Rather, they may break up or dislodge ice, allowing it to be moved by natural wind, waves or water currents against a structure. Any change in force due to a change in vessel size is negligible in view of the relatively modest change in size proposed and the similarity of hull forms.

Vessel size could influence horizontal ice loading, however, because a large ship causes larger water-level fluctuations than a smaller one traveling at the same speed. These larger water-level fluctuations might be sufficient to disrupt otherwise stable ice formations, allowing the ice to be moved by natural forces.

Vertical ice forces. A major source of damage is the vertical movement of an ice sheet. On any large body of water the water level constantly fluctuates. Coastal variations are primarily due to tides, while on large lakes, barometric pressure fluctuations, wind set-up, runoff and seiche action contribute. During periods of open water the normal fluctuations are relatively harmless. In conjunction with an ice sheet that is firmly attached to marine structures, these fluctuations can exert large vertical forces through the floating ice cover.

The structures that typically suffer the most damage are light-duty, pile-supported piers, such as those constructed for pleasure boaters. Designed for summer activity, the support piles have very little skin resistance to an upward force. When the water level rises, the buoyant ice sheet lifts the pile from the soil, and the void under the bottom tip of the pile fills in. When the water level drops, the weight of the ice is supported by the skin friction and point bearing of the pile. Since the pile is not driven into the soil as easily as it is pulled out, if the

water level continues to drop, the ice will break and the ice sheet will drop relative to the pile. The ice may then refreeze to the pile but at a lower position on the pile. This process occurs in cycles throughout the winter, gradually "jacking" the pile completely out of the soil.

DAMAGE CRITERIA

The objective of this study is to evaluate the change in incidence of damage to shorelines or shore structures due to a change in vessel size. A detailed analysis in which ship-induced forces are compared with the stability and strength characteristics of each structure or shore area could lead to a prediction of damages for known site conditions. However, the field data necessary for such an analysis are not available in sufficient detail.

Instead our analysis will center on identifying areas in which ship effects are great enough to have a potential for damage; we will then examine the influence of an increase in vessel size on those effects. The areas potentially affected by vessel passage will be selected on the basis of field experience, an analytical prediction of ship effects, and other available documentation.

The major problem in this analysis is in defining the level of ship-induced effects that is unacceptable. In the case of sediment transport we cannot realistically require that ships cause no sediment motion, even if we could predict the transient, ship-induced threshold of motion in the large, irregular channels under consideration. Small sediment dislocations should not necessarily be considered damage, particularly since natural currents, waves, recreational boating and other factors may be much more significant.

At the other extreme, ships may cause large water-level fluctuations and currents that would definitely cause unacceptable levels of sediment transport, shoreline erosion and structural damage, as well as affecting recreation and personal safety. The increase in significance of ship effects between these extremes is gradual, so it is difficult to define an unacceptable condition. The definition of damage based on vessel size is further complicated because the magnitude of ship-induced effects is heavily influenced by vessel speed, and the damage potential is affected by the water level and the site geometry and composition.

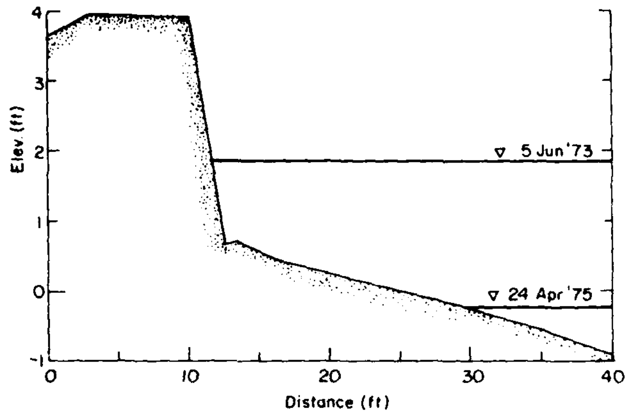


Figure 18. Relation of water level to shore profile for a site on the St. Marys River.

Vessel speed and water level are particularly significant because they are variable and, for the purpose of this study, beyond control. As shown earlier, a ship within existing size limits can cause greater damage than a larger ship if it travels faster. Although speed limits are in effect for many of the areas under consideration, several years of field experience on the Great Lakes connecting channels show that these limits are often violated. In almost all cases, properly designed and enforced speed limits would eliminate damage due to vessel passage. There are problems in certain cases, however, in allowing ships sufficient power to maintain control, and there is some debate about penalizing smaller vessels by requiring them to travel at lower velocities that are based on the requirements of larger ships.

The water level is another factor beyond the scope of vessel effects alone, and yet it is a very important consideration. As shown in Figure 18 for a shore profile on the St. Marys River, during a high-water period both natural and ship-induced forces are free to act directly on the low bluff at the waters edge. This bluff is frequently considered to be the shoreline by many property owners. If the water level was lower, the water would not act directly against this "shore." Persistent erosive forces might eventually erode the water's edge back to the bluff; in the interim the rate of material loss would be less since the mild slope would dissipate energy more efficiently and sloughing of the bluff would not occur.

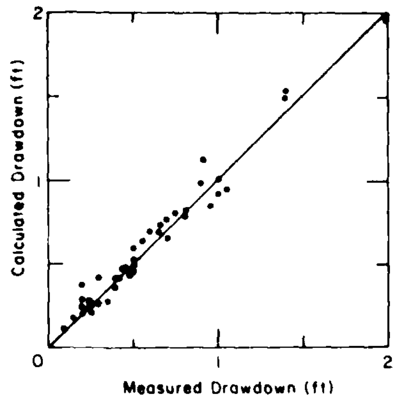


Figure 19. Comparison of measured and calculated drawdown.

At specific sites along the Great Lakes connecting channels, ship-induced drawdown, water velocity and sediment transport have been measured. These measurments would allow an empirical prediction of these parameters at these sites; unfortunately, however, these sites represent only a small portion of the shoreline areas considered in this report.

We do have sufficient information on river cross sections and ambient water velocities to predict drawdown throughout the study area. In addition, drawdown is relatively easy to measure, so that adequate field data are available to calibrate the one-dimensional model discussed earlier. The model is calibrated by applying correction factors to account for the shape of the river cross section and the effective ambient flow velocity that a ship will encounter.

The measured and calculated drawdown values for a number of measurements in channels (with shape factors ranging from 0.16 to 0.85) are compared in Figure 19. The agreement is quite good, despite the one-dimensional model and the accuracy of such input parameters as river flow velocity, channel cross-sectional area and ship draft. It is often difficult to read a vessel's draft accurately, and the draft can vary by several feet from bow to stern. The cross-sectional area and flow velocity of a channel also vary seasonally or even daily. While it would be possible to calibrate the mathematical model to represent conditions at a site on a given day more accurately, the objective here is to provide a reasonable prediction of typical vessel effects. Thus, the model was calibrated to provide an adequate representation of data collected under a variety of conditions.

Measurements of ship-induced water velocities and sediment movement are more difficult, and their values depend much more on site conditions. The one-dimensional analysis predicts only an average value of velocity. Sufficient data do not exist to extrapolate the measurements directly from specific sites to the overall study area.

Since we are concerned with shoreline and nearshore erosion, the water depths of interest are similar from site to site, even if the overall cross sections are quite different. Observations and measurements show that substantial sediment movement in the nearshore, shallow-water zone begins with drawdowns greater than about one foot, which correspond to velocity alterations of more than 2 ft/s. While this value is not exact, it provides a criterion that may be applied at sites where no data exist but where drawdown is predicted. To provide a more accurate analysis, a longer-term field study would have to be conducted.

For the case of structural damage, water levels are not as significant unless the level is high enough so that waves or ice act directly on horizontal members. However, damage to small shore structures due to open water waves has received little analysis. The data for ice conditions only concern gradual water-level fluctuations and crude estimates of horizontal forces. Ship-induced forces due to ice are largely unknown. Very small water-level fluctuations (4 or 5 inches) applied gradually may cause damage, while a transient fluctuation due to the passage of a ship of the same magnitude may pass faster than the structure can respond. Also, the major effect of vessel passage is a lowering of the water level, while the major structural damage mechanism is the uplifting force due to a rise in water level. The rise in water level due to ship passage is normally much smaller than the drawdown, rarely more than half.

As a result the criterion used in the site-specific analysis for damage to small structures will be a drawdown of 1 foot and will apply primarily to periods of navigation in ice. For an initial screening, areas will be excluded if a ship of 1200 x 130 x 30.5 feet traveling upbound at existing speed limits would cause a drawdown of less than about 1 foot. The remaining areas will then be evaluated for the change in vessel effect due to an increase in vessel size using the available details of site conditions.

SITE-SPECIFIC ANALYSIS

Based on the preceding development and a knowledge of site conditions from field experience on the Great Lakes connecting channels, the problem will now be reviewed on a site-specific basis. Due to several uncontrolled variables (vessel speed, water levels, etc.) the results here are only approximate. The calculations use low-water data (using the International Great Lakes Datum), which should be conservative. The magnitude of the ship effect would be less at the higher water levels that normally exist.

It should be stated again that the objective was not to predict damage due to vessel passage, but to predict the potential for damage due to increased vessel size. Thus, the potential damage areas listed were selected on the basis of a significant change in vessel effects, not just on susceptibility to navigation-related damage.

St. Marys River

The following description of the St. Marys River is excerpted from the U.S. Coast Pilot (NOAA 1981):

> The St. Marys River forms the outlet of Lake Superior, connecting it with Lake Huron. From Whitefish Bay, at Point Iroquois and Gros Cap, the river flows in a general southeast direction to Lake Huron at Point De Tour, a distance of from 63 to 75 miles, according to the route traversed.
>
> From Point Iroquois to the canals, a distance of 14 miles, there are six vessel courses, and the channel has a least width of 1,200 feet, with a least depth of 28 feet. Navigation around the rapids at Sault Ste. Marie is provided for by canals and locks on both the United States side and the Canadian side. Between the lower approaches of the canals and the upper end of the Little Rapids Cut into Lake Nicolet, the Bayfield Channel has a depth of 28 feet over a width varying from 1,500 to 1,890 feet.
>
> At the head of Sugar Island, about 2 miles below the canal locks, the channel divides. One route (for small craft) passes to the north and east of Sugar Island through Lake George and East Neebish, with limiting width of about 150 feet and depth of 12 feet. The main vessel route passes to the west of Sugar Island, through Lake Nicolet, with least width of 600 feet and least depth of 27 feet. Between Lake Nicolet and Munuscong Lake two channels are provided, passing on each side of Neebish Island. The west Neebish Channel, for the use of downbound traffic, passes west of the island, with least width of 300 feet and least depth of 27 1/2 feet .... The Middle Neebish Channel, for upbound traffic, leads from the head of Munuscong Lake to the east and north of Neebish Island, and has a least width of 500 feet, the westerly 300 feet has a least depth of 27 feet and

> the easterly 200 feet a depth of 21 feet.... On the vessel courses in Munuscong Lake and the lower river the depth is 28 feet or more for a least width of 1,000 feet upbound and 860 feet downbound.

The St. Marys River is shown in Figure 20. The nine reaches shown are from Carey's (1980) work and are divided according to general site conditions. The ice conditions in these reaches are described in Appendix A.

The available cross sections and site information were used to calculate the hydraulic effects of vessel passage for three sizes of ships at existing speed limits (Table 3). Two entire reaches (1 and 8) were excluded from consideration due to the size of the river cross sections. The cross sections noted are shown in Figure 20, with L and R denoting the left and right shorelines facing upstream. The empirically estimated damage criteria discussed in the preceding section were then applied to locate potential damage areas, as indicated in the last column of Table 3.

During a previous study a field survey was conducted to locate shoreline areas potentially subject to erosion (due to any cause). These sites are shown in Figure 21. Some sites were further divided into smaller reaches to reflect minor variations. The length of shoreline potentially subject to erosion in each of these reaches is given in Table 4. The table also shows which of the sites that are currently eroding are also in areas where the ship-induced damage criteria due to an increase in vessel size are exceeded.

When the criteria were exceeded for subreaches considered subject to potential erosion, further calculations were made. These results are presented in Figures 23-27, which detail the effects of the various proposed drafts and depths.

There are roughly 2.7 miles of shoreline potentially subject to erosion that also could be affected by an increase in vessel size. These areas may also be subject to erosion by natural causes (such as waves and currents); the relative significance of ship effects has not been assessed.

Only three areas along the St. Marys River with existing shore structures are potentially subject to damage due to ship effects, and then only during winter navigation. The first is near Six Mile Point (cross section 16), but here the structures have been protected with pile clusters. The second is Johnson's Point (cross section 8). Because severe damage has occurred here in the past, an increase in vessel size is not considered as

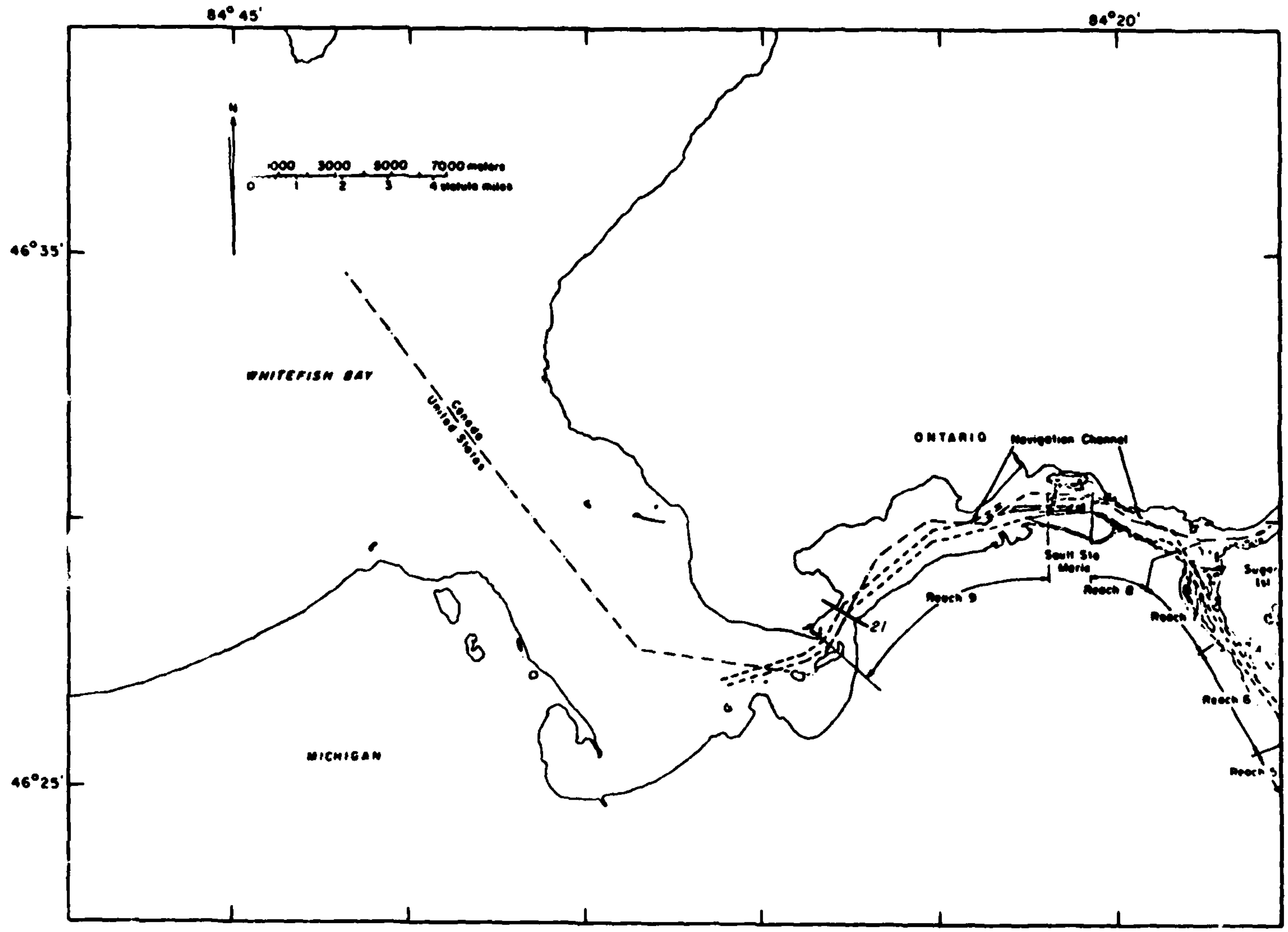


Figure 20. St. Marys River reaches and cross sections.

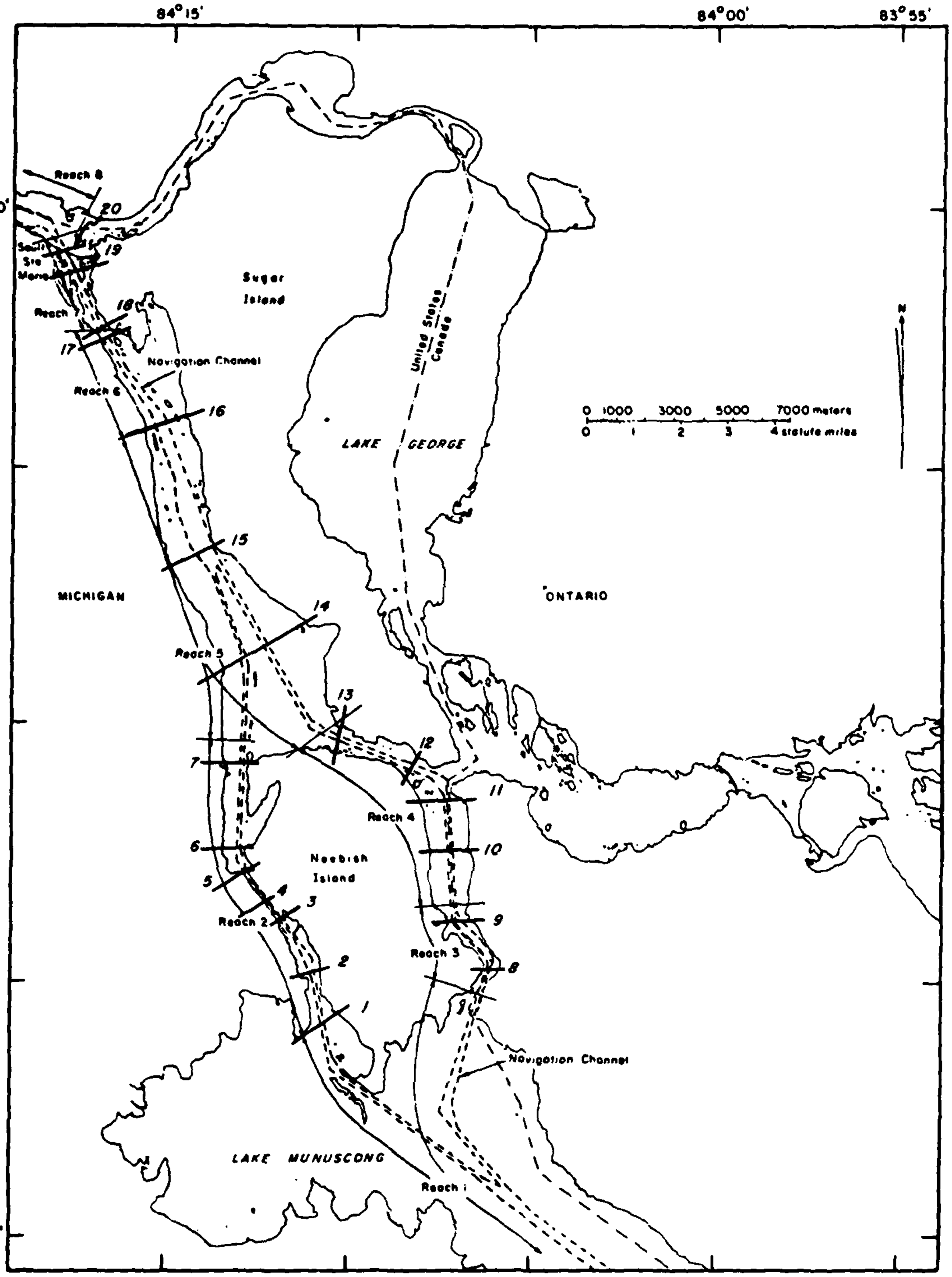


Figure 20 (cont'd).

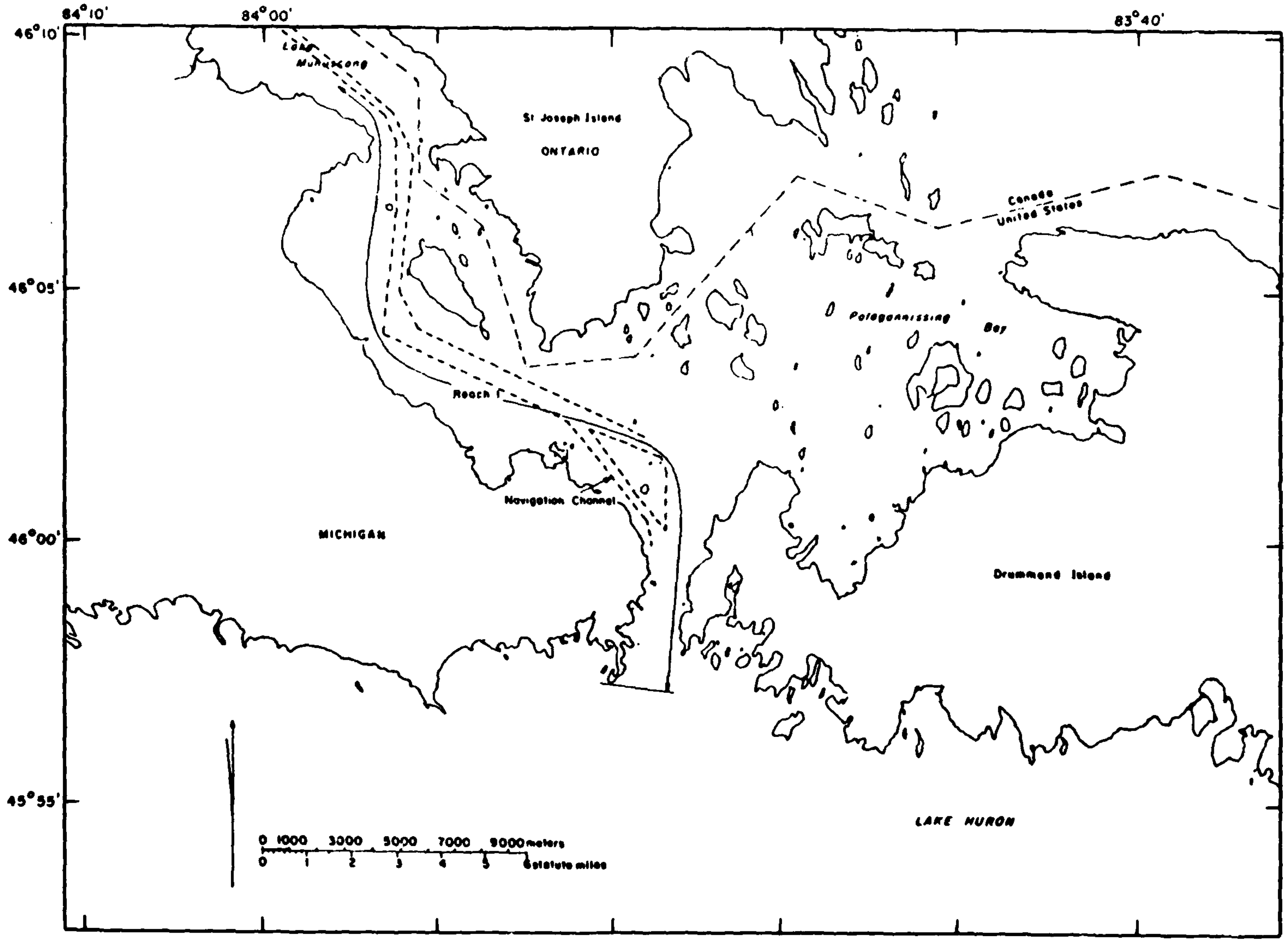


Figure 20 (cont'd). St. Marys River reaches and cross sections.

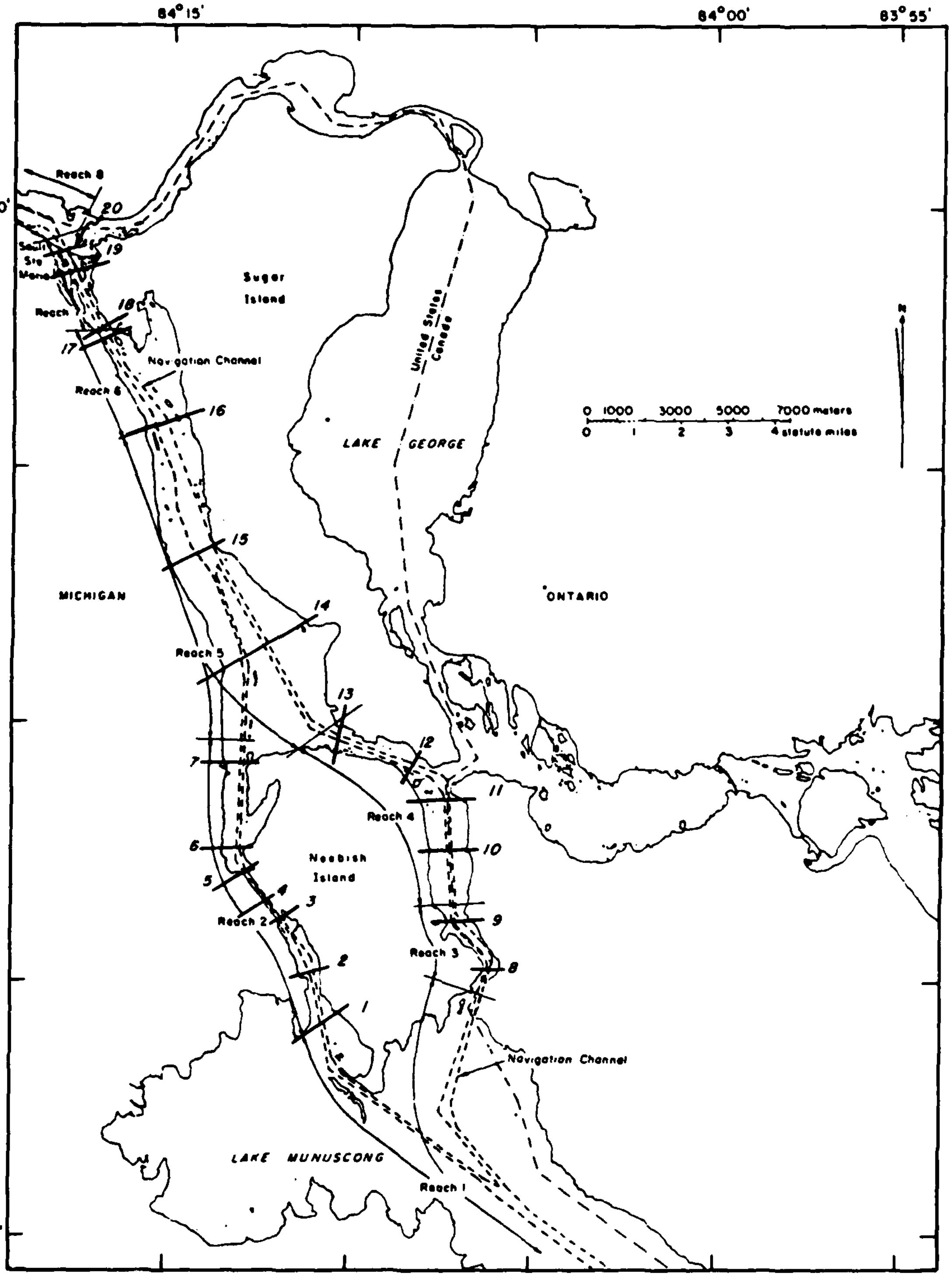


Figure 20 (cont'd).

Table 3. St. Marys River hydraulic calculations.

Reach	Section	Cross-sectional area (ft^2)	Width (ft)	Depth (ft)	S_t	Speed limit (mph)	Drawdown (ft)			Potential damage areas
							105- x 25.5-ft ships	130- x 25.5-ft ships	130- x 30.5-ft ships	
2	1	28,650	2,700	33	0.35	10	0.75	0.99	1.27	X
	2	32,381	1,730	34	0.49	10	0.82	1.08	1.40	X
	3	8,877	300	30	0.99	10	----†	----	----	X
	4	8,687	300	30	0.97	10	----	----	----	X
	5	9,037	300	30	1.00	10	----	----	----	X
	6	35,418	2,550	40	0.35	10	0.60	0.78	0.98	
	7	17,030	2,800	30	0.20	10	1.91	2.92	----	X
3	8	26,313	1,340	33	0.60	9	1.02	1.37	2.03	X
	9	37,083	3,050	31	0.41	9	0.65	0.84	1.00	
4	10	44,256	3,660	29	0.42	10	0.75	0.98	1.03	
	11	44,022	4,950	33	0.27	10	0.72	0.93	1.01	
	12	23,369	2,415	31	0.31	10	1.75	2.53	3.35	X
	13	20,187	1,655	31	0.39	10	2.24	3.56	----	X
5	14L	29,073	3,300	31	0.28	10	1.28	1.75	2.18	X
	14R	71,747	8,928	31	0.27	12	0.67	0.86	1.01	
	15L	55,330	8,850	31	0.57	10	0.18	0.22	0.26	
	15R	35,880	2,000	31	0.58	10	0.95	1.26	1.52	X
6	16L	42,498	2,272	31	0.60	10	0.77	1.01	1.21	X
	16R	96,036	8,199	31	0.38	10	0.30	0.38	0.44	
	17L	24,488	1,830	29	0.46	8/10*	1.09	1.50	1.60	X
	17R	37,332	4,510	29	0.28	8/10	0.64	0.84	0.90	
7	18	25,980	1,463	30	0.59	8/10	0.99	1.34	1.54	X
	19	17,674	727	29	0.86	8/10	1.71	2.57	2.78	X
	20	21,307	867	30	0.32	8/10	1.30	1.82	2.14	X
9	21	51,000	2,650	32	0.60	12	1.04	1.38	1.78	X

* 8 upbound; 10 downbound.

† The drawdown is very large and the model does not apply.

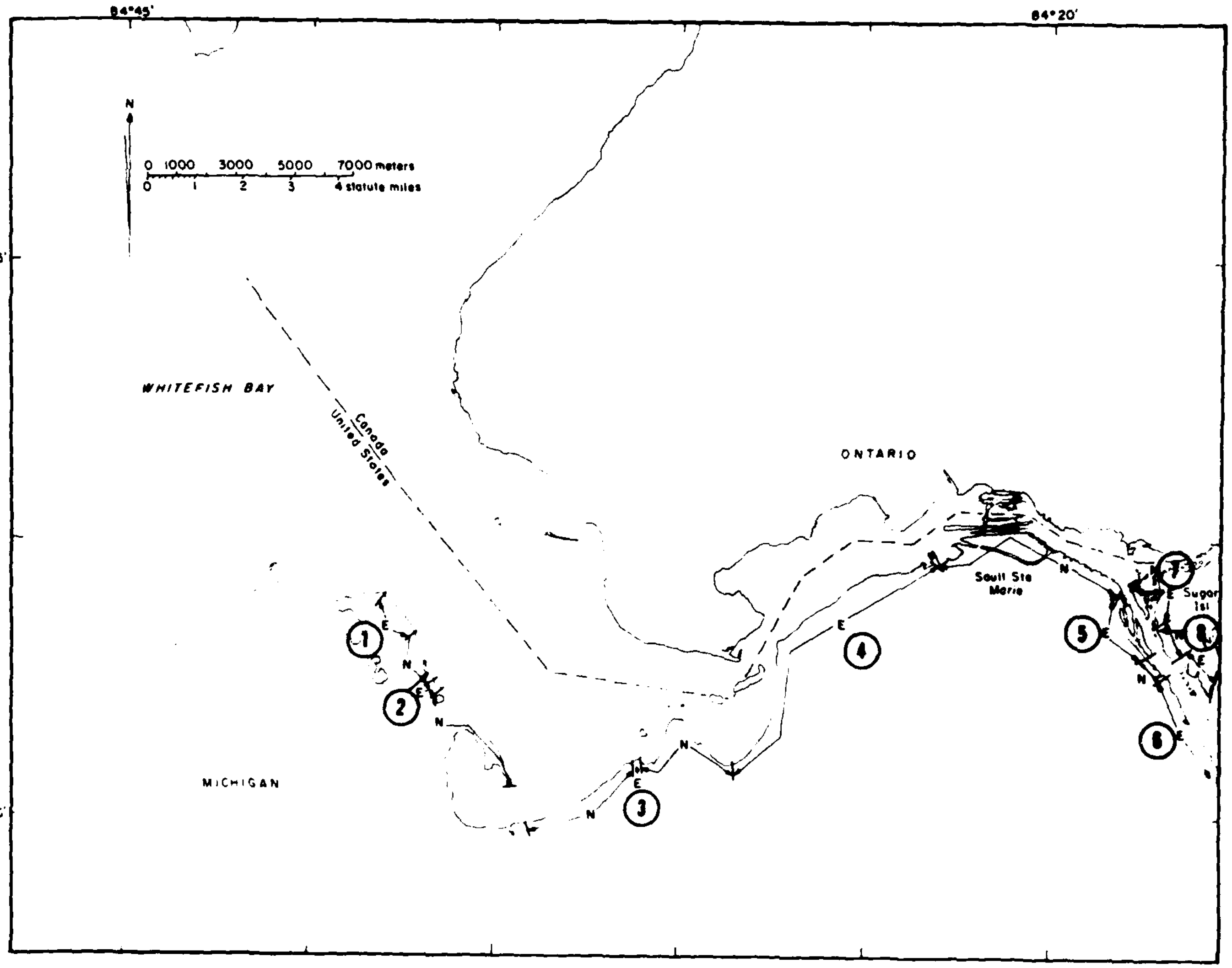


Figure 21. Potential erosion sites on the St. Marys River (*E* = *erosion possible*; *N* = *no erosion*). (From Gatto 1980.)

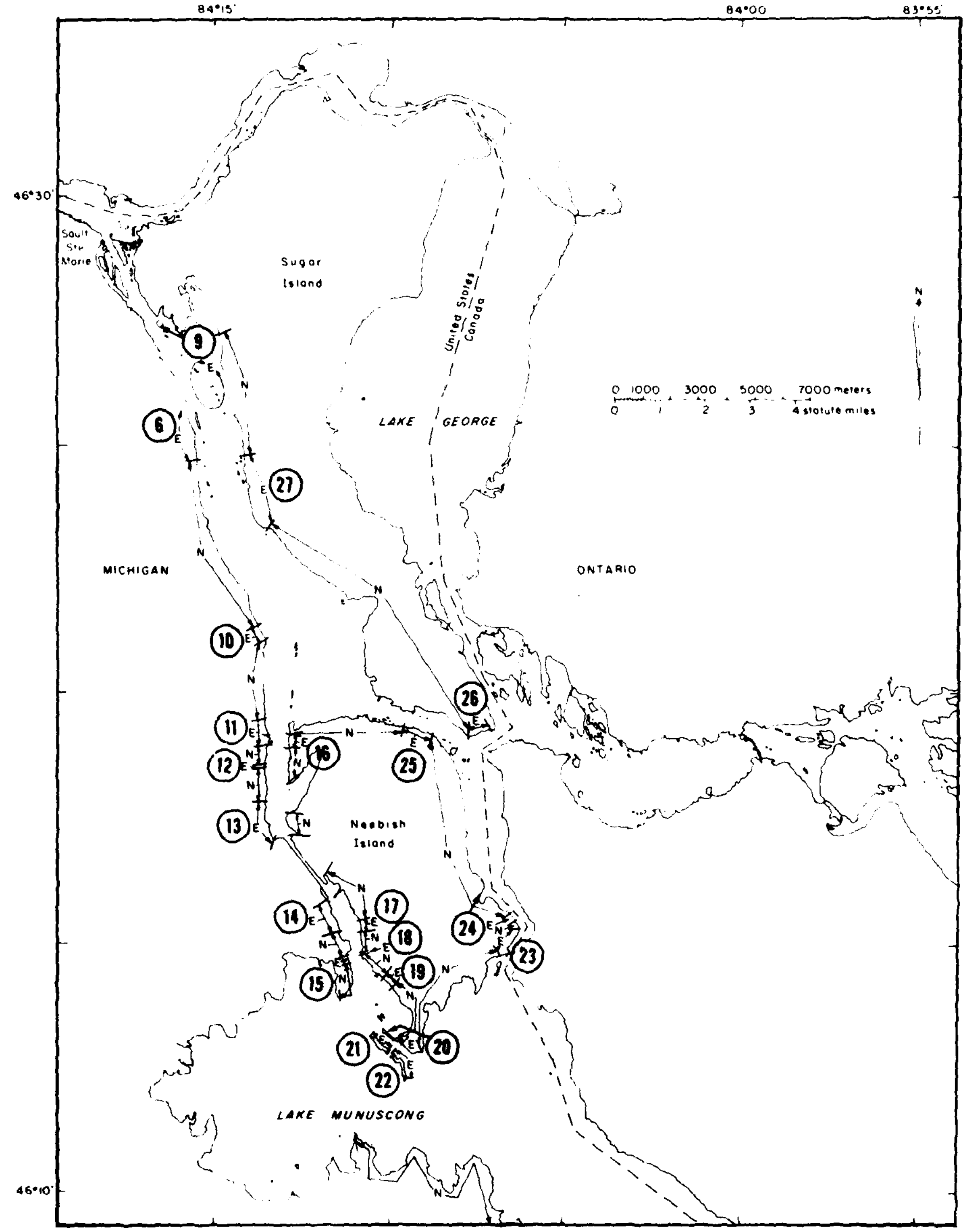


Figure 21 (cont'd).

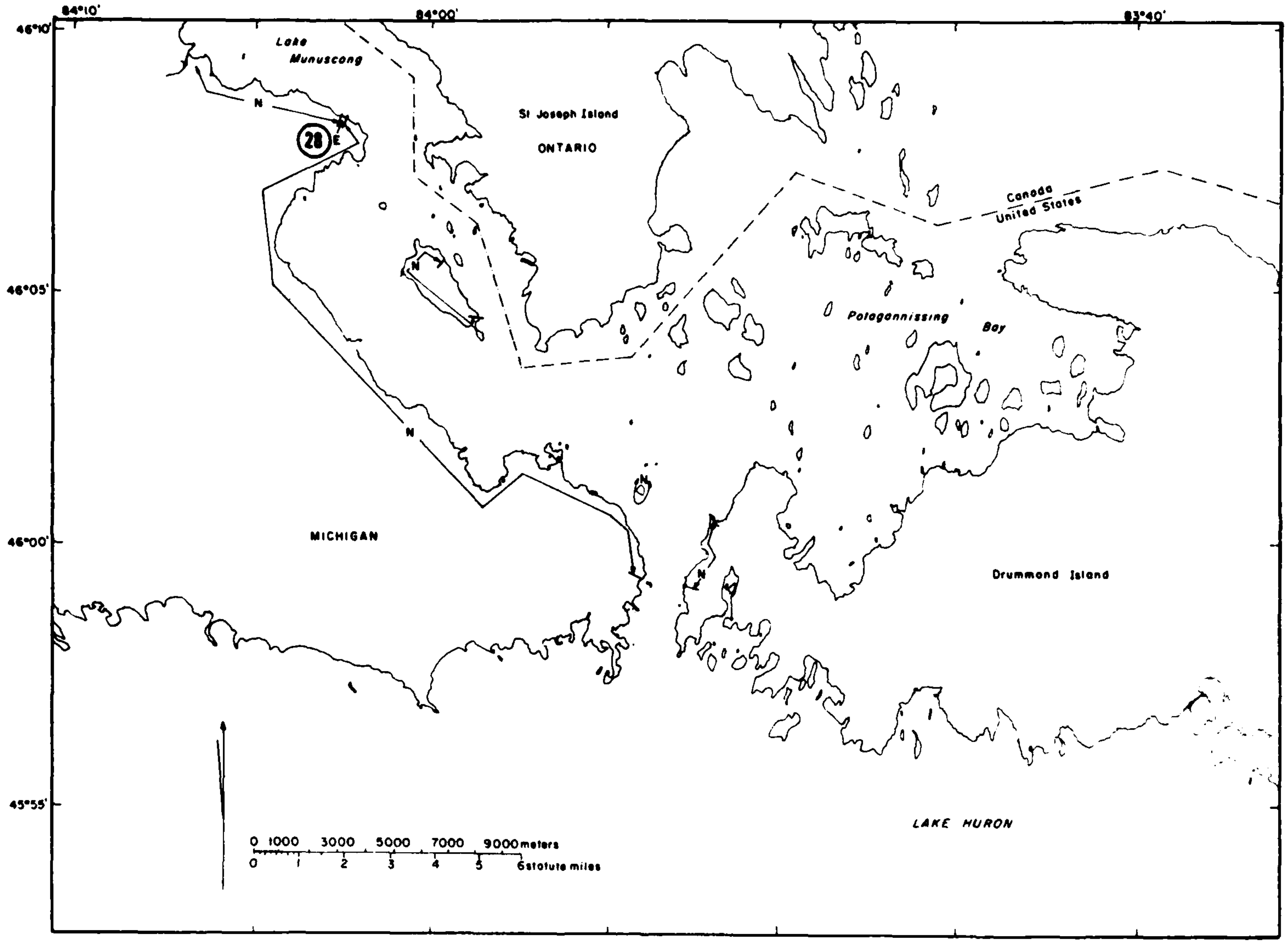


Figure 21 (cont'd). Potential erosion sites on the St. Marys River (E = erosion possible; N = no erosion). (From Gatto 1980.)

Table 4. Potentially eroding sites along the St. Marys River. (After Gatto 1980.)

Site	Subreach	Visible Changes*	Approximate Length (ft)
1		NAE	4000
2	a	NAE	400
	b	NAE	2000
3	a	NAE	200
	b	NAE	300
4	a	NAE	7000
	b	NAE	1000
	c	NAE	300
	d	NAE	50
	e	NAE	200
	f	NAE	200
	g	NAE	200
	h	NAE	300
	i	ME	400†
	j	NAE	50
	k	ME	600
	l	NAE	500
	m	NAE	600
5	a	ME	1000†
	b	NAE	4500†
6	a	ME	600†
	b	NAE	100†
	c	ME	200†
	d	NAE	300
	e	ME	700
	f	NAE	200
7	a	ME	3800
	b	ME	1100†
8	a	NAE	300
	b	ME	1400†
9	a	ME	1000
	b	ME	400
10	a	NAE	100
	b	NAE	200
	c	NAE	200
11	a	NAE	100
	b	ME	400†
	c	ME	300†
12		NAE	400
13		NAE	1200
14		NAE	200†
15	a	NAE	200
	b	NAE	500
16	a	ME	300†
	b	E	300†
	c	ME	2100†

Table 4 (cont'd).

Site	Subreach	Visible Changes*	Approximate Length (ft)
17		NAE	1400
18		NAE	300
19		ME	1500
20	a	ME	1700†
	b	NAE	1100
21	a	E	600†
	b	E	200†
	c	E	800†
22	a	E	900†
	b	E	1000†
23	a	NAE	200
	b	NAE	600†
24	a	NAE	200
	b	ME	300
25		ME	400
26		NAE	3000
27	a	ME	400†
	b	NAE	400
	c	NAE	200
28		NAE	700
			5660 = 10.7 mi

* NAE: Not Actively Eroding
ME: Minor Erosion
E: Erosion

† Erosion along these sites could be affected by an increase in vessel size. The total length that could be affected is 14,300 feet, or 2.7 miles.

important as the operating characteristics of the vessels (speed and frequency of passage). The third area is the West Neebish Channel, but this area has been closed to winter navigation. Without navigation in ice the effect of an increase in vessel size is negligible.

According to the preceding analysis there is a potential for damage due to an increase in vessel size in seven of the nine reaches shown in Figure 20. These are reaches 2, 3, 4, 5, 6, 7 and 9. We will now examine these areas in more detail.

In reach 2 the largest vessel effects are in the area known as Rock Cut, but here the channel is lined with large rock and no damage should occur. Figure 22 shows the increase in the drawdown at cross section 7 for vessels with cross sections ranging from 60 x 25.5 feet to 130 x 30.5 feet. The vessel effects at this site are quite large, with actual

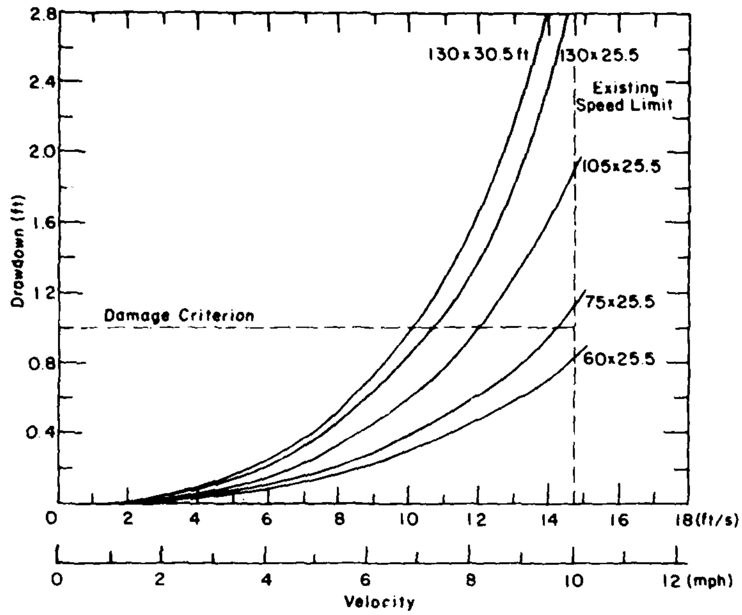


Figure 22. Vessel effects at cross section 7, St. Marys River.

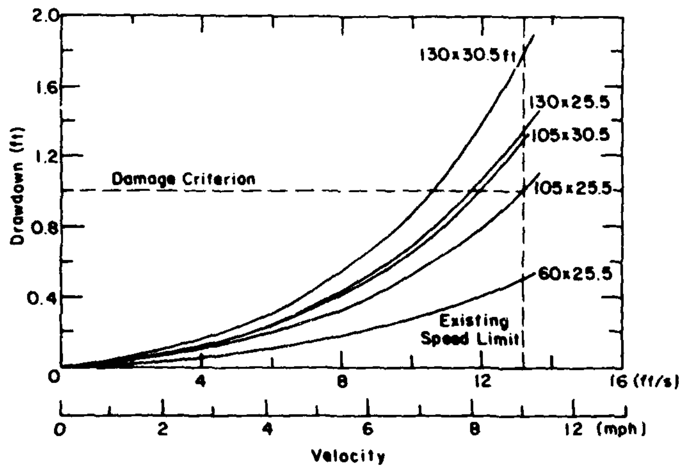


Figure 23. Vessel effects at cross section 8, St. Marys River.

measured drawdowns for existing 75-foot-beam ships often over 1 foot and sometimes approaching 2 feet. For the largest contemplated ship (130 x 30.5 feet) to meet the damage criterion, the speed limit in reach 2 would have to be reduced from 10 to 7 mph. Even the present ships with beams of 105 feet would require a reduction to 8 mph.

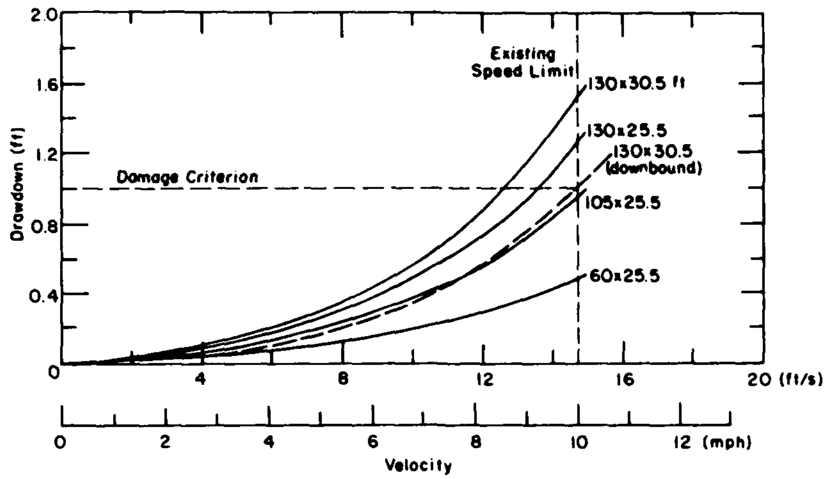


Figure 24. Vessel effects at cross section 15, St. Marys River.

In reach 3 the primary concern is shore structure damage, and there is a history of substantial damage in the vicinity of Johnson's Point. A comparison of vessel effects at Johnson's Point is shown in Figure 23. Existing ships, including those with the present maximum beam of 105 feet are within the criterion, but the 130- x 30.5-foot vessel would require that the speed be reduced from 9 to 7 mph. Figure 23 also shows that there would be little difference in vessel effects between a 130-foot-beam vessel at the existing 25.5-foot safe draft and the existing 105-foot-beam vessels at a draft increased to the contemplated 30.5-foot safe draft. The difference would be in the cost of dredging a 32-foot channel. The damage criterion would require a reduced speed limit of 8 mph with either option.

Reach 4 has a damage potential only in the Middle Neebish Channel (cross sections 12 and 13 in Figure 20). There are only 400 feet of potentially erodible shoreline and no affected shore structures; the affected reach of shoreline is gravelly and somewhat resistant to erosion. Meeting the criterion would require a reduction of the speed limit from 10 to 7 mph. If erosion should occur, protecting the shore (or even allowing erosion to occur at this remote location) might be more desirable than reducing the speed that much.

Reach 5 has only limited damage potential. As illustrated by Figure 24 for Nine Mile Point (cross section 15), even a 130- x 30.5-foot ship sailing upstream would only require a speed limit reduction from 10 to 9 mph. The same ship traveling downstream would require no reduction.

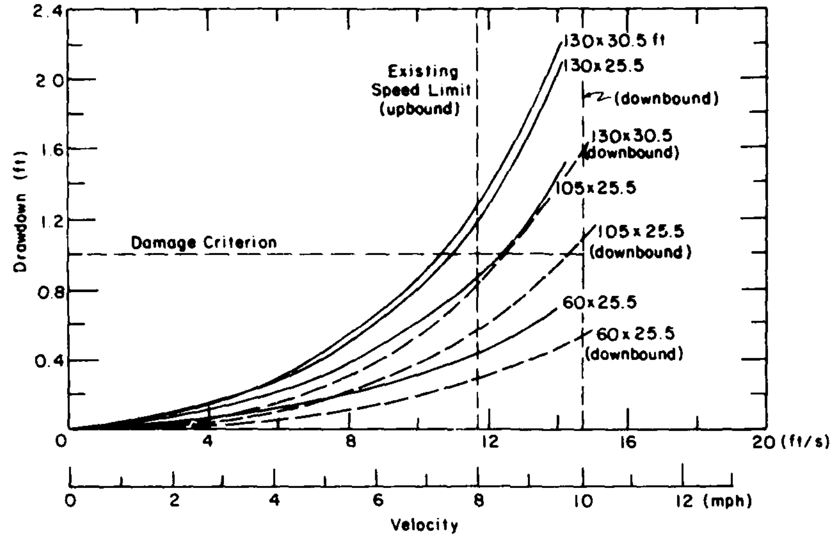


Figure 25. Vessel effects at cross section 17L, St. Marys River.

Reach 6 has some damage potential on the mainland (cross sections 16 and 17). In this reach the speed limits are 8 mph for upbound ships and 10 mph for downbound. Allowing the maximum 130- x 30.5-foot vessels would require speed limit reductions to 7 mph upbound and 9 mph downbound (Fig. 25). Due to the channel configuration and the amount of dredging required, the required speed limits for a 130- x 25.5-foot vessel would be nearly the same as for a 130- x 30.5-foot vessel. If the existing 105-foot-beam vessel draft was increased to 30.5 feet, no reduction in speed would be required.

Reach 7, known as Little Rapids Cut, is a narrow, straight channel. The speed limits are 8 mph upbound and 10 mph downbound. As shown in Figure 26, a slight reduction in vessel speed to 7 mph upbound and 9 mph downbound would allow even the largest contemplated vessel (130 x 30.5 feet) to pass the criterion. The 130- x 25.5-foot vessel would require no real change in speed limits, nor would a 105- x 30.5-foot vessel. Ships of 130-foot beam with drafts between 25.5 and 30.5 feet would exceed the criterion, but subdividing the maximum speed limit reduction of 1 mph is not realistic.

In reach 9 only a very short length of shoreline, Brush Point, has a potential for damage. This area (cross section 21) might be best served by structural protection if unacceptable erosion occurs. The present speed

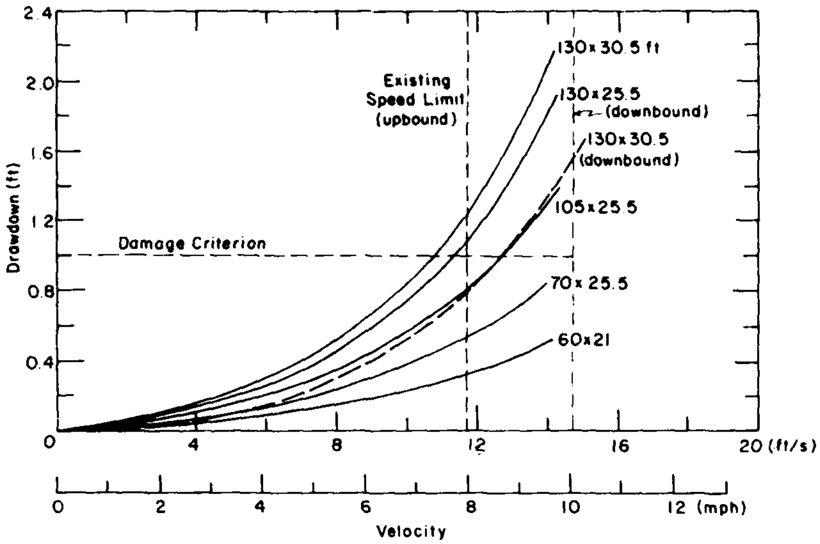


Figure 26. Vessel effects at cross section 18, St. Marys River.

limit of 12 mph is adequate for existing ships, but upbound traffic would have to be limited to 11 mph for a 130- x 25.5-foot ship and 10 mph for a 130- x 30.5-foot ship. Delineating speed limits for intermediate drafts is not warranted again, due to the short length of shoreline and the nature of the area.

In summary, there appears to be about 2.7 miles of shoreline and one area containing small shore structures where a potential for damage due to an increase in vessel size exists. Except in two cases, this potential could be eliminated by reducing the vessel speed limit by 1-2 mph. One exception is an area in reach 2 where the existing speed limit is considered high and a speed limit reduction of 3 mph would be necessary. The second is in reach 4 where structural protection may be a better solution.

St. Clair River

The St. Clair River is shown in Figure 27. The four reaches shown are from Carey's (1980) work and are divided based on general site conditions. The ice conditions in these reaches are described in Appendix A. The following description of the St. Clair River is excerpted from the U.S. Coast Pilot (NOAA 1981):

> The St. Clair River has two characteristic sections -- the lower or delta portion, and the upper or normal

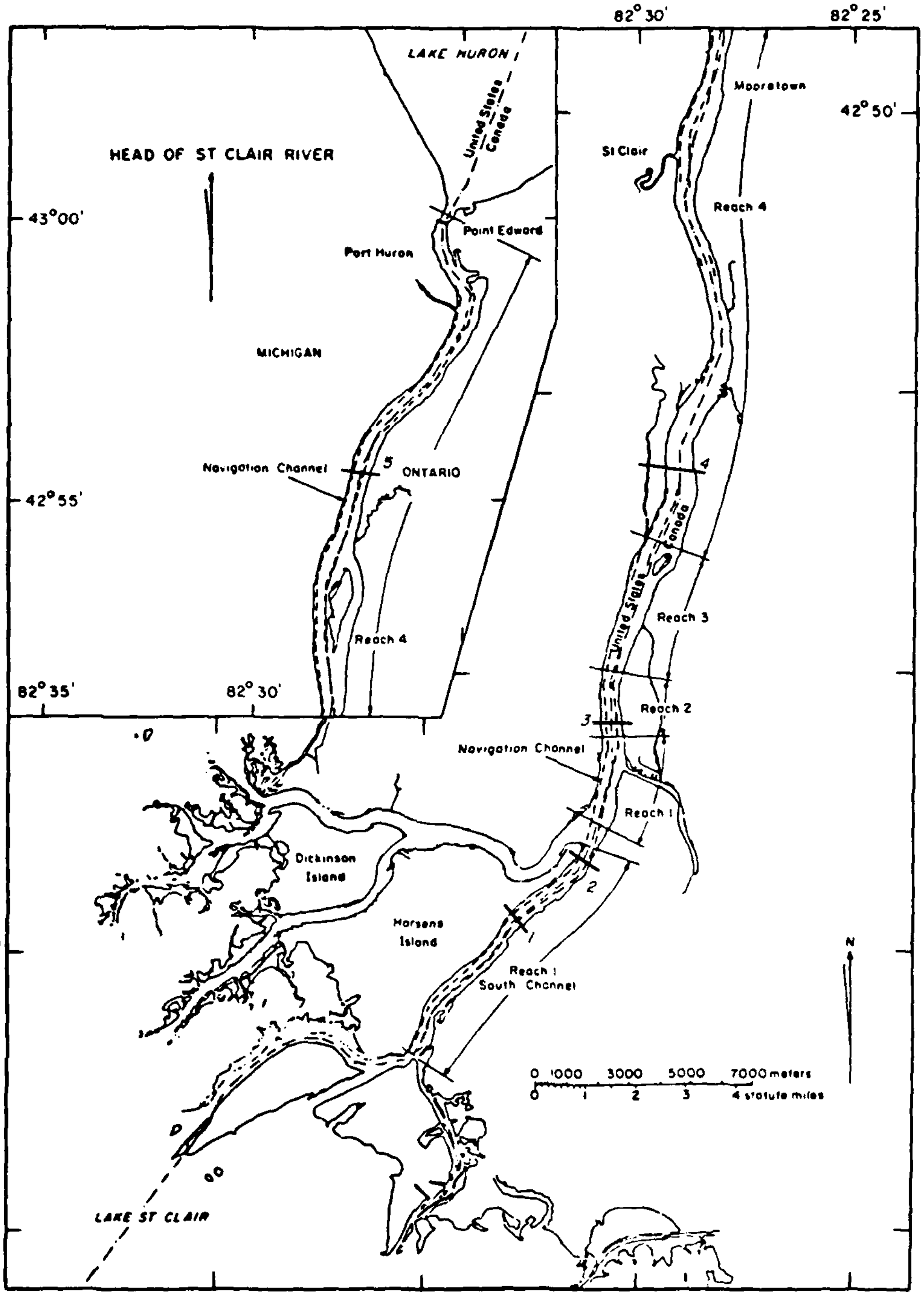


Figure 27. St. Clair River reaches and cross sections.

Table 5. St. Clair River hydraulic calculations.

Reach	Section	Cross-sectional area (ft^2)	Width (ft)	Depth (ft)	S_f	Speed limit (mph)	Drawdown (ft)			Potential damage areas
							105- x 25.5-ft ships	130- x 25.5-ft ships	130- x 30.5-ft ships	
4	5	54,570	1945	36	0.78	9/12*	0.41	0.53	0.65	
4	4	67,485	2670	38	0.63	12	0.61	0.77	0.96	
2	3	72,420	2880	37	0.68	12	0.62	0.80	0.99	
1	2		1400	27	0.82	12	2.02	----†	--	X
1	1		1600	27	0.86	12	1.51	2.04	1.77	X

* 9 upbound; 12 downbound.

† The drawdown is very large and the model does not apply.

> channel. The delta portion, commonly known as the St. Clair Flats, is the land and water area at the lower end of the St. Clair River below Chenal Ecarte, Ontario, and formed by the division of the river into a number of distributaries. The most important branch, used for through navigation, is called the South Channel, and it connects Lake St. Clair with the main river through the St. Clair Cutoff Channel.
>
> The distance from the southwest end of the St. Clair Cutoff Channel to the head of Chenal Ecarte via the South Channel is about 11 miles, making the total length of the vessel course from Lake St. Clair to Lake Huron about 39 miles.

The hydraulic effects of vessel passage were calculated from available cross sections and site information for three sizes of ships at existing speed limits. Due to the size and shape of the river cross section, the effects of vessel passage are not as pronounced as on the St. Marys River. In addition, the channel size and cross-sectional shape are quite uniform over the length of most of the river. Therefore, the hydraulic effects of vessel passage were calculated for only a few sites along the river and then for generalized minimum cross sections (Table 5).

During a previous study a field survey was conducted to locate areas potentially subject to erosion due to any cause (Fig. 28). The length of shoreline potentially subject to erosion in each of these reaches is given in Table 7. The table also shows which sites are currently eroding and where the ship-induced-damage criterion is exceeded.

This review shows that there are roughly 0.4 miles of shoreline that are potentially subject to erosion and where the damage criterion is also exceeded. These sites are all located along the South Channel at Harsens and Russell islands. These areas may be subject to erosion by natural forces as well.

The length of shoreline is small due to both the size of the river cross section and the extensive shore-protection structures already in place. Since the river cross sections are large, the influence of vessel passage is smaller and the change in damage potential due to the contemplated increase in vessel size is small. Shore structures along the St. Clair River are typically constructed better than the St. Marys River structures. In addition, ice conditions are light over much of the river.

The only area of concern for shore structures on the St. Clair extends from the head of Russell Island to the St. Clair Cutoff. This area, known

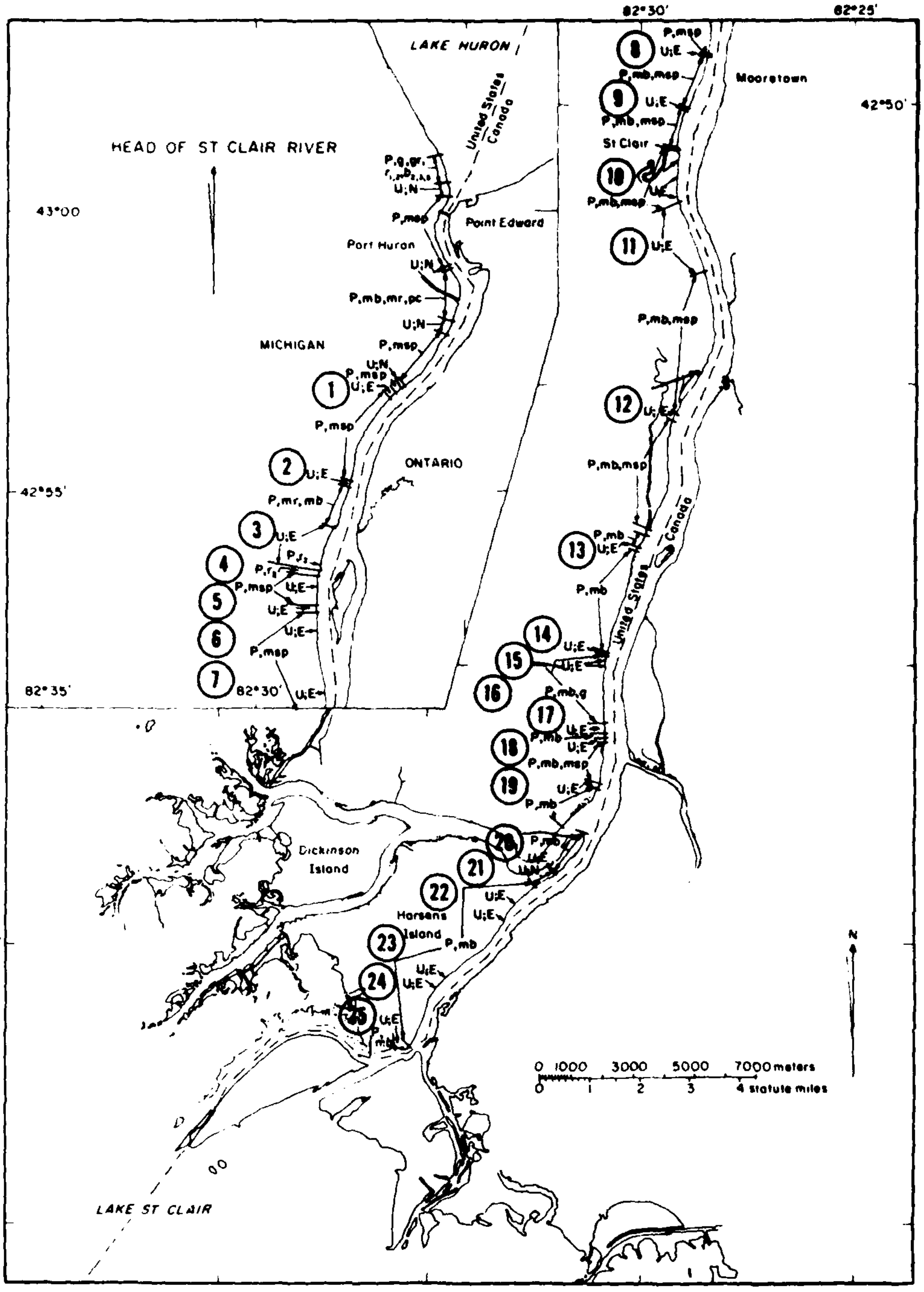


Figure 28. Potential erosion sites on the St. Clair River. The abbreviations are defined in Table 6. (After Gatto 1980.)

Table 6. Legend for symbols shown on survey maps.

Potential erosion sites

- E Erosion possible
- N No erosion

Types of shore protection

- m Mixed types (prefix)
- s Scattered types (prefix)
- P Protected
- U Unprotected
- msp Mixed combinations (usually bulkheads and riprap)
- Riprap:
  - r_1 Boulders (natural stone)
  - r_2 Concrete slabs/debris/chunks
  - r_3 Debris (cans, scrap metal, etc.)
  - r_4 Logs
- Bulkheads
  - b_1 Timber
  - b_2 Sheetmetal
  - b_3 Poured concrete
  - b_4 Concrete blocks
  - b_5 Tires
  - b_6 Cemented stone
  - b_7 Rock
- g Gabions
- tc Timber cribs filled with boulders
- gr Groins
- pc Pile clusters

as the South Channel, has numerous small structures that may be affected by vessel passage during ice conditions. These include 128 walkway docks, 54 boat houses or shelters, 72 boat hoists and a number of other structures.

Figure 29 shows the effects of vessel passage in the South Channel for several sizes of ships, from cross section of 75 x 25.5 feet to 130 x 30.5 feet. Even the smallest ship plotted exceeds the criterion by 0.2 feet when traveling at the existing speed limit.

Since shorelines and shore structures are potentially affected by vessel passage, regulating vessel speeds would solve both problems. The reductions would need to be substantial, however, since even existing ships exceed the criterion. Drawdowns in excess of 1 foot have been measured frequently.

Table 7. Potentially eroding sites along the St. Clair River. (After Gatto 1980.)

Site	Reach	Visible Changes*	Approximate length (ft)
1	a	NAE	50
	b	NAE	100
	c	NAE	200
	d	NAE	200
	e	ME	200
	f	ME	500
	g	NAE	100
2	a	NAE	50
	b	ME	50
	c	NAE	1200
	d	ME	100
3	a	ME	2000
	b	ME	800
4	a	ME	100
	b	ME	100
5	a	ME	1200
	b	NAE	100
6		NAE	50
7	a	ME	200
	b	ME	100
	c	ME	400
8	a	NAE	400
	b	NAE	100
9	a	ME	100
	b	NAE	100
	c	NAE	100
	d	NAE	100
10	a	NAE	50
	b	NAE	100
	c	NAE	50
11	a	E	1000
	b	E	2000
	c	E	200
	d	NAE	100
12	a	NAE	100
	b	ME	400
13	a	NAE	400
	b	NAE	100
	c	NAE	100
14		NAE	200
15		NAE	100
16		NAE	100
17		ME	800
18		NAE	100
19		NAE	200

Table 7 (cont'd).

Site	Reach	Visual Changes	Approximate Length (ft)
20	a	ME	250†
	b	NAE	100†
	c	NAE	200†
21	a	NAE	200†
	b	NAE	200†
22		NAE	500†
23		NAE	300†
24	a	NAE	150†
	b	NAE	150†
25	a	NAE	150†
	b	NAE	100†
			17100 = 3.23 mi

* NAE: Not Activley eroding
ME: Minor Erosion
E: Eroding

† Erosion along these sites could be affected by an increase in vessel size. The total length that could be affected is 2050 feet, or 0.4 miles.

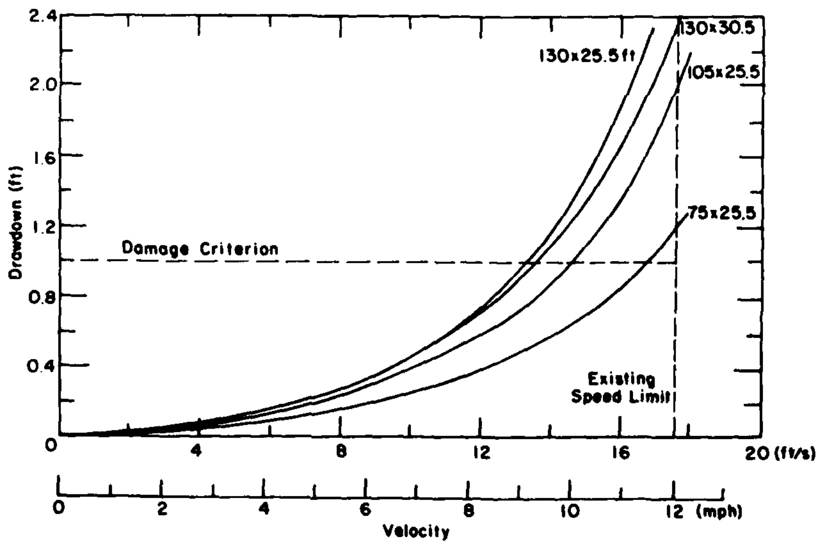


Figure 29. Vessel effects at Russell Island.

To meet the criterion the speed limit for upbound 105- x 25.5-foot ships would need to be reduced to 10 mph. The downbound limit could remain at 12 mph. Due to the dredging required for larger ships with drafts in excess of 25.5 feet, vessels with 130-foot beams and 30.5-foot drafts could safely operate under the same limit of 9 mph upbound and 11 mph downbound. As discussed in the conceptual analysis section, dredging will increase the channel cross section more than the corresponding increase in vessel cross section, thus lessening the drawdown.

In summary, a very small portion of the St. Clair River is subject to damage by an increase in vessel size. The damage potential in the South Channel could be eliminated by speed limit reductions of 1-3 mph. Existing vessels can already cause damage at existing speed limits.

Detroit River

The Detroit River is shown in Figure 30. The ice conditions are described in Appendix A. The following description of the Detroit River and its harbor facilities is from the U.S. Coast Pilot (NOAA 1981):

> The Detroit River has a length of about 32 miles from the Detroit River Light at its mouth in Lake Erie, to Windmill Point Light at the river's junction with Lake St. Clair, its head.
>
> Grosse Ile is the largest island in the Detroit River. It is about 8 miles long and about 1 1/2 miles wide, extending from about the mid-point of the Upper Livingstone Channel at the south end to about the mid-point of the Fighting Island Channel opposite the City of Wyandotte, Michigan, at the north end. The main ship channel passes to the east of the island while the westerly channel of the river, passing west of the island, has been dredged for deep draft navigation from the north down to a point about 2 1/2 miles above the lower end of the island. This dredging has developed the Trenton Channel. Below the south end of the Trenton Channel, the natural river has no deep draft navigable channel into the lower river below Grosse Ile.
>
> The Rouge River constitutes a branch channel of the harbor of Detroit, and the related industrial district also extends down the west channel of the lower Detroit River to Ecorse, Wyandotte, and Trenton.... This river discharges into the Detroit River at the southerly limits of the city of Detroit. Its natural course is generally about 150 feet wide in the lower river, below the junction with the short-cut canal...and about 300 feet wide from the canal to the turning basin near the Ford Motor Co. docks. The mouth of the river is flanked by large industrial plants.
>
> The short-cut canal, an artificial connection, about 3,000 feet long, originally constructed by private interests,

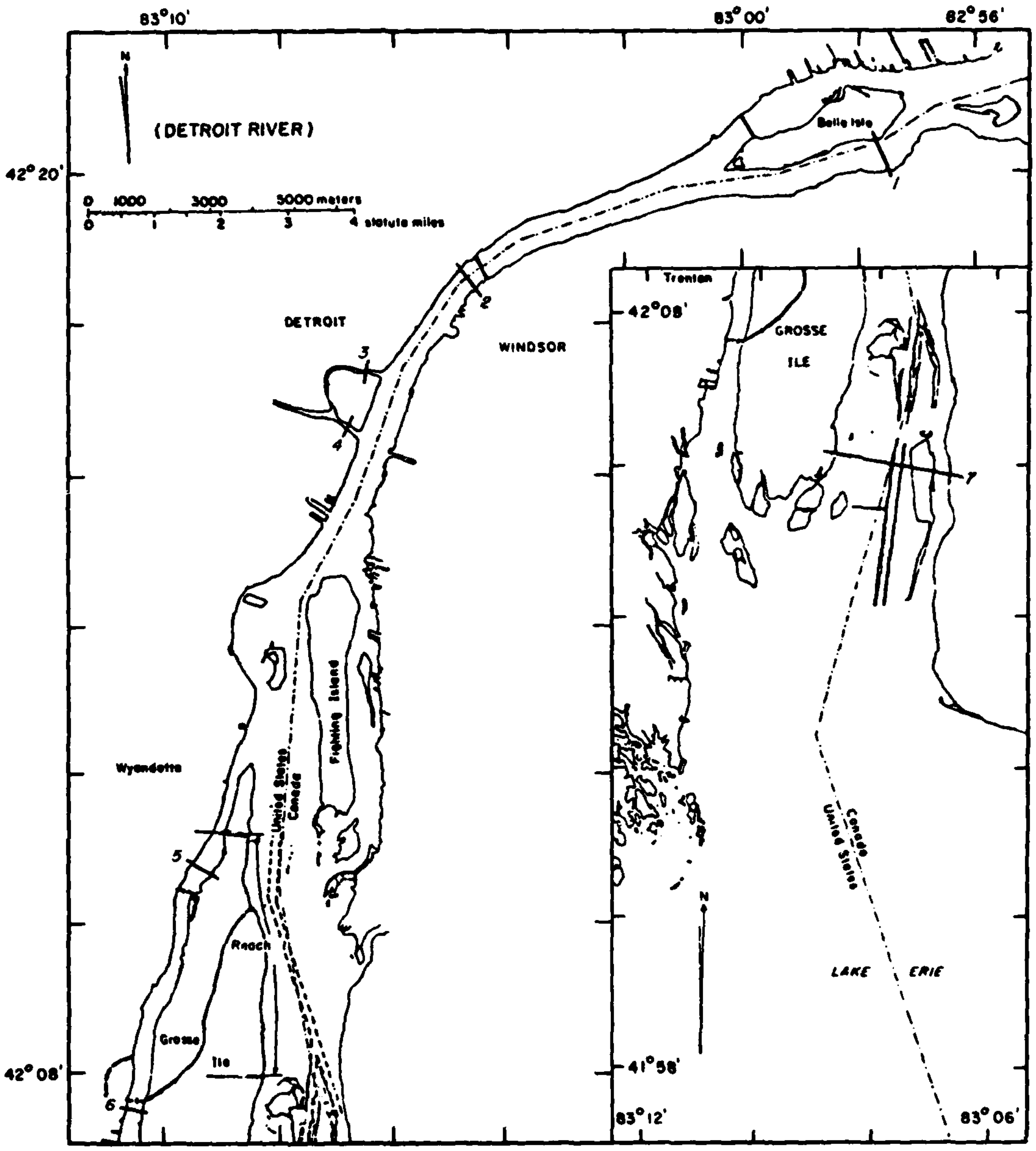


Figure 30. Detroit River reaches and cross sections (Lake St. Clair to Lake Erie).

Table 8. Detroit River hydraulic calculations.

Section	Width (ft^2)	Depth* (ft)	S_f	Speed limit (mph)	Drawdown (ft) 105- x 25.5-ft ships	130- x 25.5-ft ships	130- x 30.5-ft ships	Potential damage areas
1	2050	36	0.79	12/14†	0.69	0.89	1.01	
2	1975	47	0.7	12/14	0.55	0.70	0.86	
3	150	21	0.9	4	----**	----	----	X
4	300	21	0.9	4	0.97	1.58	1.71	X
5	2000	27	0.8	10††	0.66	0.86	0.81	
6	1000	26	0.7	7††	0.74	0.99	0.96	X
7	600	27	1.0	12	----	----	----	

* Existing channel dimensions are listed. The minimum channel depth considered is 1.5 feet greater than the ship draft.

† 12 upbound; 14 downbound.

** The drawdown is very large and the model does not apply.

†† No specific speed limit; the speed shown is the maximum within the damage criterion.

extends from the Detroit River about one mile below the mouth of the River Rouge in a straight line to a bend in the River Rouge, thus avoiding an S-shaped curve in the lower river course and shortening the distance to upstream points by 5600 feet. This short-cut canal in conjunction with the natural Old River Channel, has created Zug Island. This island is occupied entirely by the facilities of several large industrial corporations.

Available cross sections and site information were used to calculate the hydraulic effects of vessel passage for three sizes of upbound ship at existing speed limits. Because the river cross sections are large, the effects of vessel passage are slight. In addition, the channel size and cross-sectional shape are quite uniform along the river. Therefore, the effects of vessel passage were calculated at only a few sites along the river (Table 8).

The results for cross sections 1 and 2 show calculated vessel-related effects to be less than the criterion. The depths here and in much of the Detroit River are greater than at many of the cross sections in the other rivers, so the ship effects are typically less.

For the River Rouge (cross section 4) the criterion is exceeded for the posted 4-mph speed limit. However, the existing channels are much too small for the sizes of ships considered in this report and would have to be enlarged substantially. Furthermore, the River Rouge area is completely

dominated by heavy industry, with the shore and shore structures highly developed, so damage due to vessel passage should not be a significant problem.

The Trenton Channel near Grosse Ile (cross section 6) has no speed limit listed. However, it is a narrow, dead-end channel in which large ships move slowly, often under tow. The speeds listed in Table 8 for Trenton and Wyandotte are the maximum speeds for those channel areas that would still meet the damage criterion. This maximum allowable speed is less than 1 mph more for the 105-foot-beam ship than for the 130-foot-beam ship, regardless of draft. In addition, these velocities are well above actual ship speeds observed in the area.

The Livingston Channel (cross section 7) exceeds the damage criterion but is excluded because it is a dredged channel with rock dikes along its sides. These dikes are artificial, resistant to erosion, and serve to isolate ship effects from nearby shorelines.

During a previous study a field survey was conducted to locate shoreline areas potentially subject to erosion due to any cause (Fig. 31). The lengths of shoreline potentially subject to erosion in each of these areas is given in Table 9. None of these areas are considered to be potentially damaged by the contemplated vessel size increases.

While there are over 100 small, privately owned shore structures (docks, boat hoists, etc.) along the river, none are located in areas where the potential for damage would be increased due to the passage of larger vessels.

CONCLUSIONS

The potential for shoreline or shore structure damage due to an increase in vessel size was reviewed on both a conceptual and site-specific basis. While it is difficult to predict damage potential, it was possible to estimate where problems might occur if vessel sizes are allowed to increase. Because the increase in vessel size considered in this study is relatively modest, it was possible to exclude most of the study area from consideration. For example, no damage would be anticipated on the Detroit River due to an increase in vessel size. There are several areas on the St. Marys and St. Clair rivers where the shore or shore structures may be damaged, but these areas form a small part of the overall system.

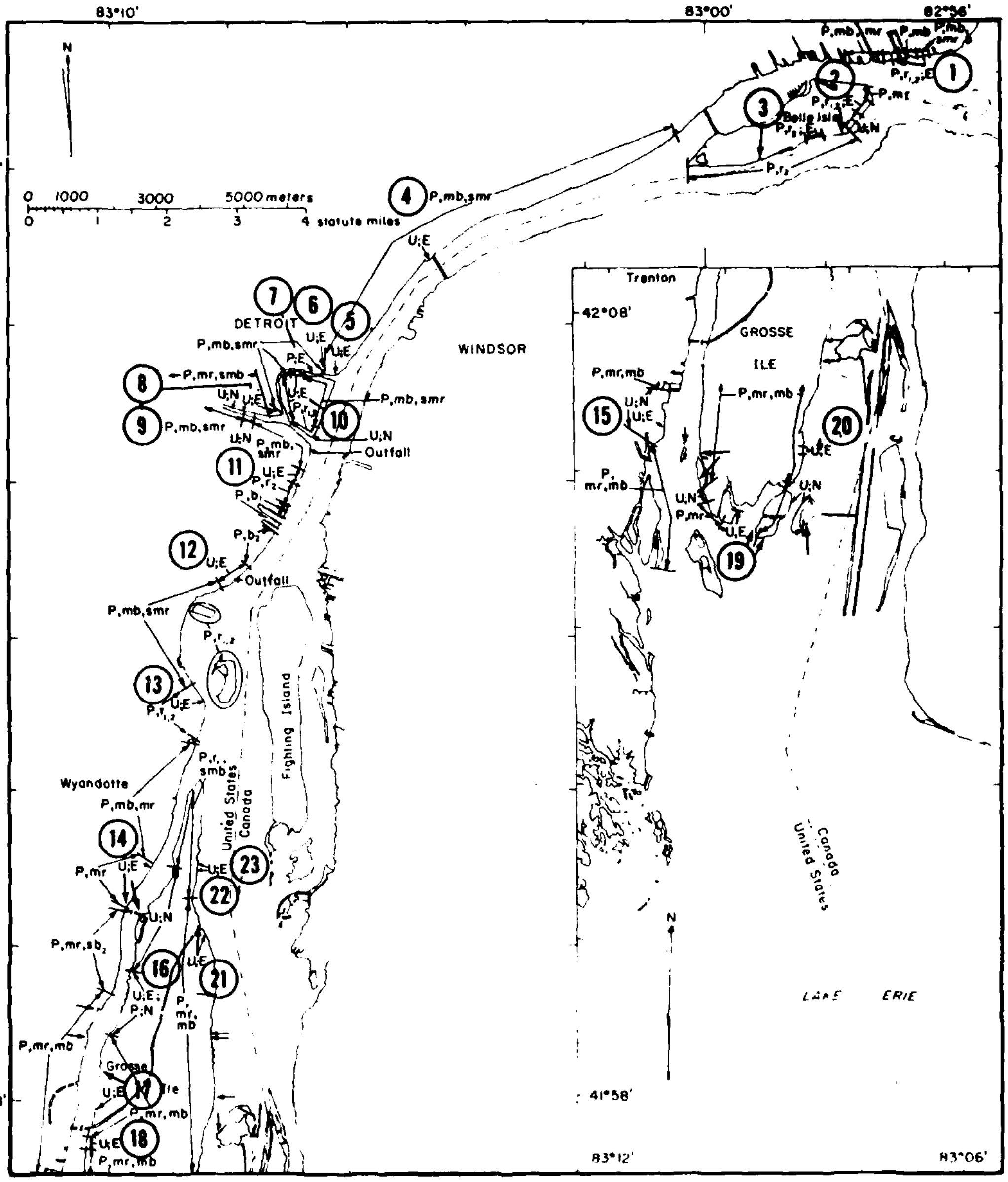


Figure 31. Potential erosion sites on the Detroit River. The abbreviations are defined in Table 6. (After Gatto 1980.)

Table 9. Potentially eroding sites along the Detroit River.

Site	Subreach	Visible Changes*	Approximate Length (ft)
1	a	NAE	200
	b	NAE	1100
2	a	NAE	300
3	a	NAE	100
	b	NAE	50
	c	NAE	50
4		NAE	200
5		ME	50
6		ME	150
7		ME	50
8		ME	1000
9		ME	50
10		ME	3800
11		NAE	3000
12		NAE	1400
13		NAE	100
14	a	NAE	50
	b	NAE	100
	c	ME	200
15		ME	2000
16	a	ME	800
	b	ME	50
	c	ME	50
	d	ME	1000
	e	ME	300
	f	ME	400
	g	NAE	100
17	a	ME	600
	b	ME	800
18		ME	1000
19	a	ME	2500
	b	ME	800
	c	ME	800
	d	ME	1100
	e	ME	2000
	f	ME	2000
	g	ME	3000
20	a	ME	700
	b	ME	1500
21	a	ME	300
	b	NAE	1000
	c	NAE	100
	d	ME	600
	e	NAE	50
	f	NAE	50
	g	NAE	100
	h	NAE	150
	i	NAE	150
22		ME	200
23		ME	100
			36550 ft = 6.92 mi

* NAE: Not Actively Eroding, ME: Minor Erosion, E: Erosion

The objective of this study was to evaluate the effect of an increase in vessel size. Thus, areas subject to ship-related damage were excluded from consideration if the potential for damage was relatively unaffected by vessel size. Also, even if an area is affected by an increase in vessel size, other natural factors (such as waves or currents) might be more significant.

While larger ships can definitely cause more damage, the potential for damage caused by the size increases considered here is significant only in severely restricted channels. By far the most significant factor in ship-related damage potential is vessel speed. In almost all areas the effect of an increase in vessel size could be eliminated by decreasing vessel speed by 1-2 mph.

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APPENDIX A: ICE CONDITIONS ON THE ST. MARYS, ST. CLAIR AND DETROIT RIVERS

St. Marys River

According to Carey (1980) the ice conditions in reach 1, from Lake Huron to the head of Lake Munuscong, are essentially as in a lake, with extensive shore-fast ice and a continuous, uniform, stable ice cover. The ice cover may move vertically due to water-level fluctuations on Lake Huron, and in the spring, drifting floes may move horizontally due to wind action. Thick shore ice forms in reach 2, and natural uplift due to water-level fluctuations on Lake Huron move this ice vertically. Broken ice moves through the reach during spring breakup.

In reaches 3, 4, 5 and 6, thick, stable ice forms a continuous cover. During spring breakup, broken ice moves through these reaches.

Reach 7 is a transition zone between a generally stable, continuous ice cover downstream and generally open water upstream. A stable ice cover and shore ice form in the side cannels and around the islands. Under natural conditions the Little Rapids Cut may have shore ice or may become ice-covered. Broken ice passing downstream through open water progressively fills the Little Rapids Cut with compacted ice.

Reach 8 generally has open water with light shore ice. Shore ice and often a more extensive ice cover form in reach 9. This ice moves vertically as a result of wind set-up in Lake Superior and Whitefish Bay. It may move horizontally under the influence of wind during breakup.

St. Clair River

According to Carey (1980) the south channel in reach 1 is subject to the formation of stable shore ice, extending generally out 6 feet or to the end of the shore structures. Otherwise, it becomes ice-filled only after Lake St. Clair freezes over, and floe ice coming down the St. Clair River progressively covers the channel from the south end northward. Horizontal movement of the shore ice is negligible. Vertical movement of the shore ice, due to wind-induced changes in the level of Lake St. Clair, is confined to the early season when shore ice is thin. Thus, the vertical

forces resulting from this movement are negligible. Also, large level changes do not generally occur due to ice jamming, since jams form upstream of the South Channel. During the spring, ice moves out to the channel along a shear zone at the offshore edge of the shore ice. Later, when the shore ice is melted, the moving floe ice generally remains confined to the deeper (>6 feet) parts of the channel and does not interfere with shore structures.

Ice jams consistently form in the main channel in this reach, due to the accumulation of ice floes coming downstream from Lake Huron. The frequency and severity of jamming is highly dependent on the supply of ice from Lake Huron. Pressure in the floe field forces ice pieces up on edge and produces piling and layering, so that the thickness of the jam may reach 8-10 feet. The jam stabilizes by freezing together, and when weather or river conditions allow it to break and release, the movement and turning of the ice damage structures. Level changes resulting from the jam may be as much as a 1- to 2-foot increase in stage. This causes uplift forces on adfrozen structure piles. Ice conditions in reaches 2 and 3 are the same as in reach 1, but to a diminished degree.

Reach 4 is upstream from locations where ice jams commonly occur. Shore ice normally forms in this reach, but the principal form of ice in the reach is unjammed ice floes and brash floating downstream. Ice floes may be released in quantity at times from Lake Huron, or they may be sparse as a consequence of the formation of a natural ice bridge at the mouth of Lake Huron. Ships penetrating the ice bridge can increase the amount of floating ice in the reach, until the ice bridge re-forms. Little or no damage to structures generally occurs due to ice north of Fawn Island at the southern end of the reach.

Detroit River

According to Arctec (1978) a level ice cover is never formed in the main channel of the Detroit River. Generally the river is ice-free except for small amounts of shorefast ice and occasional jam-ups of ice floes from Lake St. Clair in the Peach Island-Belle Isle area and in the Fighting Island-Grosse Ile area. The Trenton Channel and the mouth of the Rouge River also experience occasional ice jams, particularly under the influence of an easterly wind. The upper Rouge River develops a level ice cover generally under 6 inches thick, even in severe weather.